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**A STUDY
ON THE APPLICATION
AND INSTRUMENTATION
OF VISUAL PERCEPTION
FOR
SPACE EXPLORATION**

FINAL REPORT

(NASA CONTRACT NO. NASw-441)

27 AUGUST 1963

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
400 MARYLAND AVENUE, S.W.
WASHINGTON 25, D.C.

APPLIED RESEARCH LABORATORY

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STUDY ON THE APPLICATION AND
INSTRUMENTATION OF VISUAL
PERCEPTION FOR SPACE EXPLORATION

Final Report

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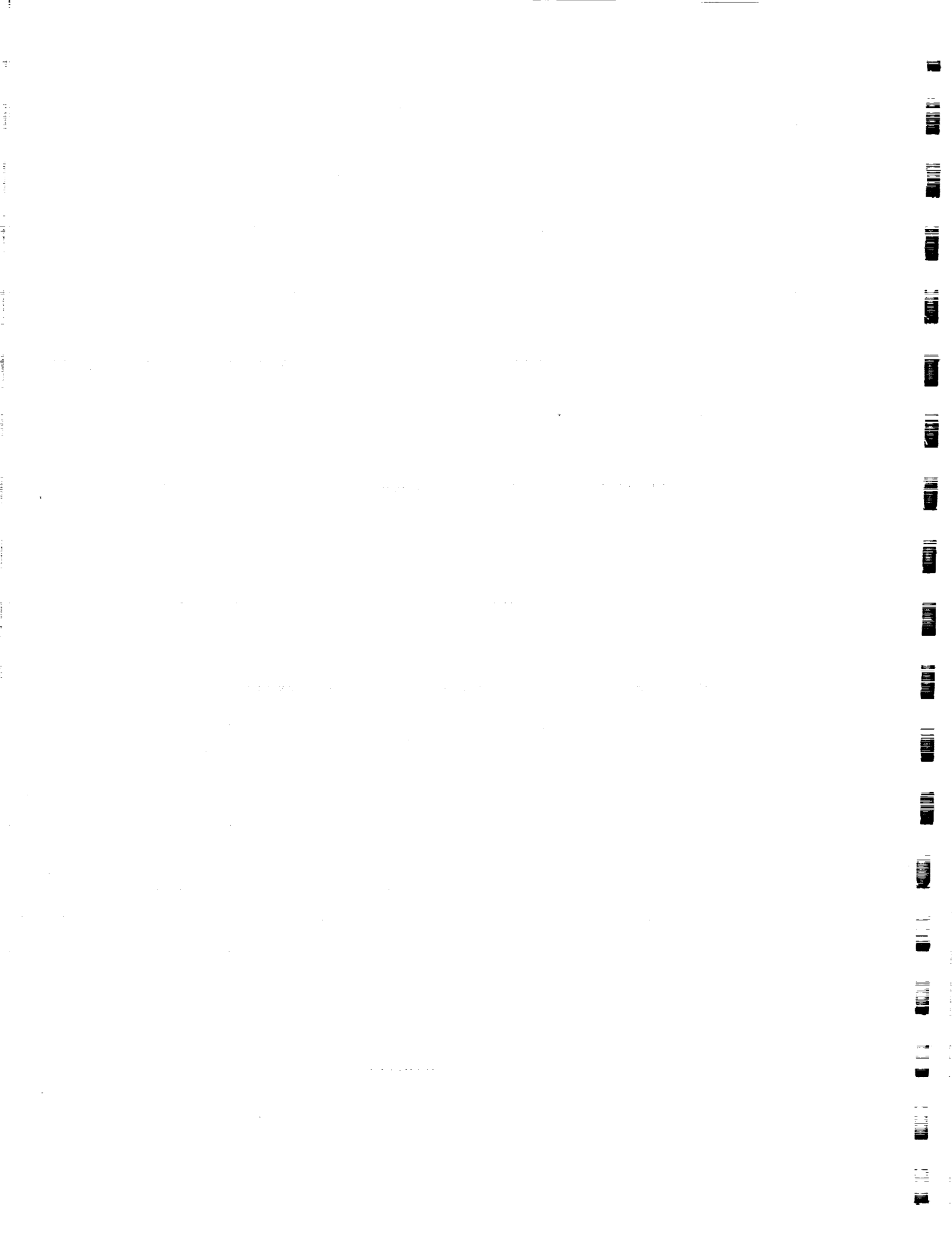


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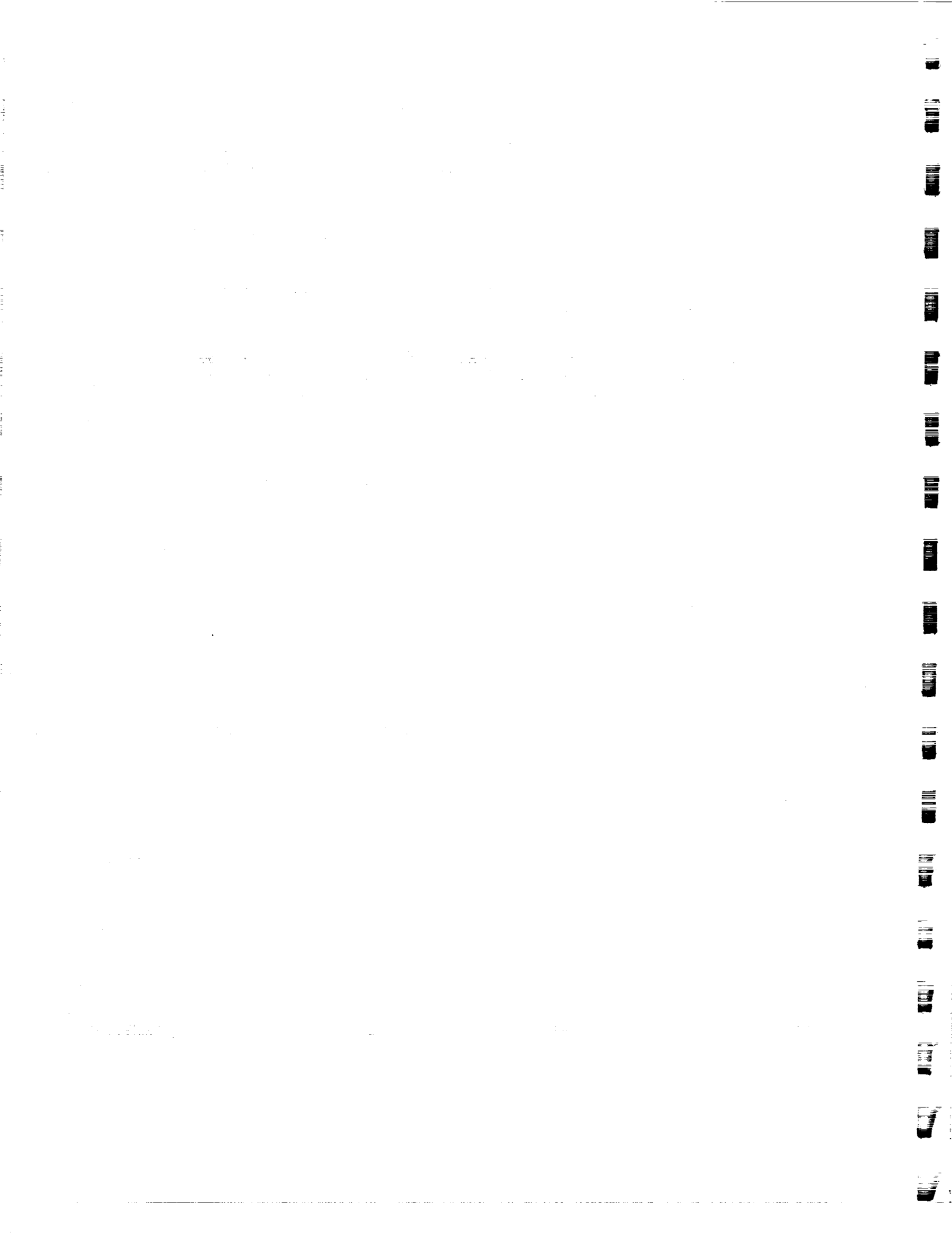
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SECTION 1

SUMMARY OF PROGRAM

The purpose of the present contract is to investigate the utility of human visual and color perception concepts in space exploration, with particular emphasis on the application of the Yilmaz theory of color perception. A study was performed to determine the area of need for generalized spectral, visual, and color perception in space exploration. The study showed that there was great need in space exploration for optical instruments, television systems, etc., more closely duplicating the wide adaptation and accurate spectral discrimination capabilities of human vision. To design such systems requires a clearer knowledge of the operation of the human visual system, particularly the processes of visual adaptation.

The research effort was therefore directed to achieve a more precise explanation of the operation of the visual system. This effort was concentrated in two areas:

- 1) Extension of the Yilmaz theory of color perception^{3,4} to develop a quantitative definition of the transformations of color vision adaptation.
- 2) Extension of the Biernson Spectral Scanning theory⁵ to develop a description of the receptor mechanism of color vision.

These two efforts were finally fused by incorporating the Yilmaz color adaptation transformations within the Spectral Scanning theory.

Let us first review our efforts to develop a quantitative explanation of visual adaptation. The phenomenon of chromatic adaptation is very poorly understood. The startling two-color projections by Land¹⁷ served to demonstrate more clearly than had been recognized in the past how much our chromatic sensations are determined by simultaneous contrast effects. An excellent summary of the status of our understanding of visual adaptation has been presented in a recent article by Stiles.¹⁸ In essence, there is no general theory for predicting what colors are

observed under different states of adaptation, although approximate empirical formulas have been developed that are useful in certain cases.

While at Sylvania, Dr. Huseyin Yilmaz^{3,4} developed a theoretical model of the adaptation process of color vision, which provided a basis for a fresh attack on the chromatic adaptation problem. His essential principle is as follows:

In order for object colors to remain invariant with changes of illumination, the changes of color sensation with changes of illumination must follow an approximately relativistic transformation in perceptual coordinates.

Yilmaz reasoned that evolutionary forces would cause the eye to develop in such a manner that it would be optimized for discriminating among natural objects independently of the characteristics of the illuminant. The above principle of color transformation was proposed to satisfy this requirement.

Helson and Judd¹⁹ developed in 1940 an approximate model for the transformations of chromatic adaptation based on the UCS (uniform chromaticity scale) chromaticity diagram. They found empirically that the achromatic point shifts with adaptation to different points on the diagram, and that the color perceived from a given light depends approximately on the vector drawn from the achromatic point to the chromaticity coordinates of the light, the angle of the vector approximately defining the hue and the length approximately defining the saturation. The achromatic point corresponds roughly to the average chromaticity of the background. This transformation provides a first approximation of adaptation effects for small shifts of the achromatic point, but runs into difficulty for larger shifts.

The important aspect of the relativistic color transformation of Yilmaz is that it predicts that the points on the chromaticity diagram expand about the achromatic point as the achromatic point moves toward the edge of the diagram. The effect of this expansion is that the maximum saturation sensations are essentially the same regardless of how close the achromatic point moves toward the edge of the diagram.

On this program we worked to apply the Yilmaz theory to derive a general quantitative description of visual adaptation. A major problem was the clarification of the perceptual color coordinates in which the relativistic transformations must hold. Our effort in this regard took the following approaches:

- 1) A theoretical investigation of the characteristics of the perceptual color coordinate system was made.
- 2) Data from chromatic adaptation experiments was plotted on various chromaticity coordinate systems to observe trends. In particular, we looked for evidence of expansion of the points of the chromaticity diagram about the achromatic point when the achromatic point moved toward the edge of the diagram.

Our efforts in approach (1) are summarized in Section 4.2 and those in approach (2) are summarized in Section 4.3.

We observed relativistic-shift effects in our work, but they tended to be masked by random variation in the data. The data was obtained from very accurate measurements made by Burnham, Evans, and Newhall²⁰ at Eastman Kodak Company, and so the random variations are apparently due to real variations of the vision of the observers.

Our studies led us to believe that we should place more emphasis on the spectra themselves, rather than to restrict our thinking to tristimulus values. Judd* has pointed out that a tristimulus colorimeter is quite inadequate for color specification. If two samples have about the same reflectance spectrum, normal observers can detect reliably very small differences in the spectra. However, if the spectra are matched to three primaries, the variation of the settings of the primaries for a normal observer are at least five times greater than the variation corresponding to the least detectable difference in spectra. For this reason, in a color matching experiment, random variations can occur in the tristimulus values which would represent extremely large

*Reference 21, p. 123.

variations of color sensation if different spectra were used to produce the tristimulus values. Preliminary investigations of chromatic adaptation based on the spectra themselves were made and yielded promising results.

In our study of the perceptual color coordinates of vision we found that white appears to act as a positive sensation and black as a negative sensation (or vice-versa). This suggested that the receptor might operate as a balanced detector, delivering a positive signal for a light of luminosity greater than that of the average over the field of view, and a negative signal for a light of luminosity less than that of the average. This characteristic would occur if the bleaching of visual pigment in the receptor generated a positive current and the regeneration of visual pigment generated a negative current.

A negative current caused by the regeneration of visual pigment would produce shot noise that would limit the threshold sensitivity of the receptor under conditions of light adaptation. As was reported by Stiles,¹⁸ up to now there has been no adequate explanation for the relationship between visual threshold and visual pigment concentration, and this has represented a serious question in the explanation of visual adaptation. An evaluation of this hypothesis that the receptor acts as a balanced detector is presented in reference (10) by George Biernson, entitled "On the Relationship Between Photopigment Concentration and Visual Sensitivity." The report shows that the hypothesis agrees very well with experimental data on the visual threshold under light adaptation.

The second part of our research effort was directed toward the extension of the Spectral Scanning theory of color vision by Biernson.¹¹⁻¹⁴ The original vaguely defined Spectral Scanning concept⁵ was extended to yield the following model of the receptor mechanism of color vision. Dielectric waveguide modes in the outer segments of the cones produce different spatial distributions of energy across the photodetector region for different wavelengths. An electrical or chemical field scans across the visual pigment and controls the release of electrons from

molecules that have been excited by light. The scanning action generates a modulated waveform, in which the d-c value carries the luminosity information, the first harmonic carries the blue-yellow information and the second harmonic carries the green-red information. The distinction between blue and yellow and between green and red depends on the phase of the harmonic relative to the scanning field. The waveform is demodulated and filtered in the retina to produce separate pairs of d-c signals of opposite polarity, which give rise to the white-black, blue-yellow and green-red color sensations.

The Spectral Scanning theory was studied in terms of available experimental data on color vision and was found to be in excellent agreement. It was found that the spectral patterns that are required to satisfy color mixture data are qualitatively consistent with what would be expected from waveguide mode effects.

Our separate research efforts on the receptor mechanism of color vision and the transformations of visual adaptation began to progress in the same direction. Both efforts pointed to the conclusion that chromatic adaptation must be performed by the visual system in terms of multi-dimensional spectral information, which is more like the original spectra themselves than like the three-dimensional color signals. In contrast the classical concept of color vision is that the complete visual process is three-dimensional. Up to now, experiments to define chromatic adaptation have been based on three-dimensional color matching measurements. The concept that visual adaptation is performed in terms of multi-dimensional spectral data is a radical departure from the prevailing thinking in the field of color vision, and suggests entirely new approaches to the study of visual adaptation.

From this line of reasoning it has been possible to combine the Yilmaz theory of color perception with the Spectral Scanning theory to yield the very simple model of visual adaptation that is given in Appendix C. From the Yilmaz theory, we have been able to show that visual adaptation should satisfy the following equation in order for it to behave in accordance with a Lorentz-type relativistic transformation with changes of illumination:

$$S = \frac{L - L_o}{L + L_o} \quad (1-1)$$

Where S is the sensation (represented by the neurological signal), L is the luminance of the sample, and L_o is the luminance of the background to which the receptor is adapted. This equation, strangely enough, was first delivered (in a slightly different form) by Adams and Cobb²² in 1922 from empirical reasoning, and is considered by Judd* to give a good description of adaptation.

If the detection process in a receptor behaves in accordance with Eq. (1-1), a relativistic transformation is achieved for changes of intensity of illumination. When the Spectral Scanning principle is added, a relativistic transformation is also achieved for changes in the chromaticity of the illuminant. Thus by means of Eq. (1-1) we can incorporate the Yilmaz theory of color perception within the Spectral Scanning theory to achieve a precise description of the visual adaptation process. It can be shown that the functions predicted by these two theories can readily be satisfied by plausible mechanisms within the visual receptors.

Papers on the Spectral Scanning theory were presented at the 1963 Bionics Symposium¹⁵ at Dayton, Ohio on March 20, 1963 and at a meeting of the Optical Society of America¹⁶ on March 27, 1963 in Jacksonville, Florida.

* Reference 21, p. 226.

SECTION 2

REQUIREMENTS OF PROGRAM

2.1 STATEMENT OF WORK

The statement of work² on the program is as follows:

The Applied Research Laboratory will provide all necessary personnel, materials, equipment and facilities and shall use its best efforts in conducting theoretical and experimental investigations of the utility of human visual and color perception concepts to space exploration. These investigations shall be in accordance with the Applied Research Laboratory Proposal No. B-32-61 and shall include

- a) Estimates of the area of need for generalized spectral, visual, and color perception in extra-terrestrial exploration, and a determination of expected spectral, visual, and color phenomena to be encountered under space conditions, including studies leading to the characterization of surfaces by means of visual and/or electromagnetic inspection.
- b) Experimental methods of simulating normal color vision, super color perception, and non-visual spectral region perception, including the construction of such laboratory perceptrs as may be required.

The referenced Proposal¹ No. B-26-61 describes the Yilmaz theory of color perception and discusses the application of its principles in space exploration.

2.2 RESULTS OF PROGRAM

An estimate of the area of need for generalized spectral, visual, and color perception in extra terrestrial exploration (in accordance with (a)) was made, and is described in Section 3. This study concluded that there is a strong need for optical imaging equipment in space exploration that more closely achieves the high spectral resolution and wide adaptation range of human vision. As part of this study an investigation was made of expected spectral, visual, and color phenomena to be encountered under space conditions, which is described in Section 3.3.

By means of color perception the eye has a very effective mechanism for characterizing different surfaces, and (as indicated by the last item of Requirement (a)) it is desirable to develop equipment that can employ similar principles in characterizing objects. In our study of means of characterizing surfaces by visual and/or electromagnetic inspection we had to evaluate the manner in which the eye characterizes surfaces.

Our studies indicate that each receptor of the eye acts as a spectrum analyzer, but reduces the spectral information into a three-dimensional interpretation which we call color. The spectral information is processed in the receptors in terms of spectra (by what is called visual adaptation), and this processing allows the following

- (1) Accurate compensation for the spectrum of the illuminant, so that the eye sees essentially the reflectivity spectrum of the object.
- (2) Accentuating spectral differences of neighboring objects, in what is called contrast enhancement, which enables the eye to detect very fine differences in object reflectivity spectra.

Thus the data processing performed in the retina represents a very efficient means of reducing the complex spectral information into a simple yet accurate three-dimensional characterization of the object. This same type of processing should therefore be useful in electronic sensing devices.

The primary effort on the program was directed toward conducting investigations leading to the application of human visual perception in space exploration. In accordance with Applied Research Laboratory Proposal¹ No. B-26-61 we began our efforts by extending the Yilmaz^{3,4} theory of color perception. This was supplemented by work on the Biernson Spectral Scanning theory⁵ of color vision. Together the two theories were developed to form a theoretical model which appears to be able to explain the high spectral accuracy and wide adaptation capabilities of human vision. This model is sufficiently defined to form the basis for designing equipment that should eventually be able

to achieve the same type of spectral discrimination and adaptation performance as human vision.

Work on the extension of the Yilmaz theory of color perception is described in Section 4, and work on the Spectral Scanning theory is described in Section 5.

Section 6 describes experimental work in the simulation of normal color vision and super color perception, in accordance with Requirement (b) above.

SECTION 3

AREA OF NEED FOR GENERALIZED COLOR PERCEPTION

3.1 SUMMARY OF AREA OF NEED

The first task on the contract was to estimate the area of need for generalized spectral, visual, and color perception in extra-terrestrial exploration. The study indicated that human vision is vastly superior to present photographic or television equipment in spectral discrimination. Therefore, there is great need for designing new photographic and television sensing equipment that more closely approximates the performance of human vision. Such equipment would be useful for:

- (1) Replacing the human operator at remote stations where it is infeasible to use a human;
- (2) Extending the spectral discrimination performance of human vision into the infrared or ultra-violet.

Under normal lighting conditions, the human eye can make discriminations among ten million different shades of object color. It can adapt to compensate for large changes of chromaticity and intensity of the illuminant. The ratio of minimum to maximum power detectable by the retina is nearly one billion to one. The ratio of light intensities that the human eye can distinguish instantaneously in a given scene is much greater than one thousand to one.

In contrast, for achromatic colors photographic color film has a dynamic range of about 60 to one, and a color television tube has a dynamic range of about 20 to one. As the chromaticity is increased the dynamic ranges drop drastically. Because of these limitations, neither color television nor photographic equipment can begin to compare with human vision.

Quarterly Report⁶ No. 1 presented a discussion of the limitations of present photographic and television equipment relative to human vision, and concluded that much better performance should be achievable if we could apply the adaptation principles of human vision. However, we do not yet understand how human vision performs its adaptation,

and basic study of the visual process is needed before the application to hardware can be commenced. Section 3.2 shows that such a study would also yield many other advantages in space exploration.

As a part of this problem of estimating the area of need for generalized color perception in space exploration, a survey was made of the expected spectral phenomena to be encountered under space conditions, which is described in Section 3.3. This survey concluded that there is a great need for equipment that will extend the high spectral discrimination capability of human vision into the infra-red region and possibly the ultra-violet region, because there is so much spectral information there that could be used. This provides another impetus for our study of human color vision.

3.2 USEFULNESS OF MODEL OF HUMAN COLOR VISION

The visual environment in space is radically different from that on earth. Intense glare from direct and reflected sunlight can not only seriously impair visual performance but could also permanently damage the eye. While being subject to conditions of intense glare in one direction, the eye must be able to make stellar observations and observations of distant space vehicles in another direction. This requires that the eye be dark adapted to achieve adequate sensitivity. High spectral discrimination capabilities will also be needed in this high-glare environment in order for vision to be effective in recognizing specific landmarks on the lunar surface.

A theoretical model of human vision that accurately predicts the performance of visual adaptation would be very useful in designing vision aids for space exploration, such as protective glasses and optical filters for minimizing glare and maximizing discrimination capability. The model would be invaluable in establishing the spectral characteristics of visual marking devices used for guiding the space vehicle to launch sites. It would provide a more reliable basis for predicting the effectiveness of human vision in landing and rendezvous maneuvers.

A great many optical observations in space will be performed

by remote photographic or television equipment, and in many cases the data will be telemetered to an observer who will evaluate it. Present techniques do not provide the quality of optical data from remote sensors that is needed for efficient space exploration. In particular, color information would be very useful. For example, color photographs of cloud formations from the Mercury capsule (presented at the March 1963 meeting of the Optical Society of America) have shown that much greater information concerning the relative heights of cloud formations can be obtained from color photographs than from black-and-white. Conventional color television techniques however are quite inadequate for such scientific operations.

A more accurate theoretical model of human vision would be very useful in the design of optical image processing system. The model could provide a much more satisfactory basis for optimization of the various stages of processing of the visual data, including the parameters of the camera, telemetry device, and visual display. In particular, we will probably want to build into the equipment automatic mechanisms for adapting it to various conditions of illumination, and the design of such mechanisms would be greatly facilitated by a theoretical model of human vision that adequately explained visual adaptation.

Our present color sensing devices, such as colorimeters and color television cameras, are based on the principle of the Trichromatic theory of color vision. Considerably more accurate spectral discrimination, with a much wider dynamic range, should be achievable from optical instruments based on the principle of the Spectral Scanning theory. Early applications of the Spectral Scanning principle would probably be for instruments requiring low angular resolution, such as colorimeters or image tracking devices. However, with the growth in micro-miniaturization techniques, we can look forward to the eventual design of optical devices based on the Spectral Scanning principle that will approach the acuity of human vision.

Optical sensing devices will have numerous application in space exploration for guidance, television, tracking, and communication.

Therefore, a theory of vision that can provide a basis for improving the design of such devices will be very valuable.

3.3 SPECTRAL ENVIROMENT IN SPACE

To provide background for directing our research efforts on color vision toward the problems of space exploration, one of tasks on the contract was the "Determination of expected spectral, visual, and color phenomena to be encountered under space conditions." Our effort in this area was devoted to a literature survey. The following is a summary of our findings.

Night Glow and Aurora: A great deal of effort is being devoted to the study of air glow and aurora from the earth, and this effort will undoubtedly be extended to observations from satellites. References (23) and (24) discuss auroral radiation in the infra-red and references (25) discusses it in the far ultra-violet. Reference (26) discusses night glow spectra in the infra-red. Reference (23) contains a collection of papers of a symposium on aurora and airglow. Of particular interest in reference (23) is a discussion of an eight-color photometer for the study of the illumination of the night sky or in the visible region.

Sun, Stars and Planets. Considerations of the spectra from stars and planets could be useful in space guidance for (1) locating specific stars or planets, and (2) discriminating against a stellar background when trying to locate another space vehicle. For the latter task, infra-red data is particularly valuable. Measured data on infra-red spectra is given in reference (27) and reference (28) gives calculated spectra from 0.1μ to 100μ .

More detailed studies of the spectra of sun, stars, and planets will be needed for scientific study of the chemical constituents of the individual bodies. In particular we will be interested in ultra-violet (below $.29\mu$) and for infra-red (above 14μ) which do not penetrate the earth's atmosphere. Reference (29) discusses infra-red spectroscopy of planets and stars, and reference (30) discusses the infra-red, visible and ultra-violet environment of interplanetary

space, including the sun, corona, planets, and scatter by interplanetary dust and gas. Reference (31) discusses results of infra-red spectroscopy in evaluating chemical constituents on the sun, on the moon, and in the earth's atmosphere. Reference (32) discusses the results of spectroscopy measurements in determining the constituents in the atmospheres of the planets. References (33) and (34) give infra-red spectra measurements of Mars and Venus in the 8μ to 13μ range.

Close Observations of Moon and Planets We cannot at present predict what type of spectra we will observe when we approach close to the moon or planets. However, we can make estimates from extrapolating the spectra on earth, which are discussed below.

Detailed Study of Minerals in Space The search for minerals on the moon and other bodies of the solar system will be important in supporting exploration activities, and spectral information will be useful. Reference (35) discusses the colors of various minerals. References (36) and (37) discuss fluorescence of minerals, which might be important because of the high ultra-violet radiation in space. In particular radioactive elements are often fluorescent. On the other hand, fluorescent radiation might not be detected unless the object is shielded from the direct visible sun rays, because of the visible reflected energy.

Spectra of Earth A great many observations from space will be made of the earth in locating specific objects for navigation purposes, in mapping areas, etc. Therefore, the spectra of objects on earth are important for space exploration. Besides, we can extrapolate from some earth spectra what we may expect in space.

Reference (38) gives a very good summary of the spectra in the visible region and CIE color coordinates of natural objects on earth, including water, bare areas and soils, and vegetative formations. Detailed data of spectra in the visible region (and also in the near infra-red up to 1.1μ) and CIE color coordinates of different types of trees are given in reference (39). Reference (40) presents visible range spectra of desert surfaces, including sand, salt bed, volcanic surface, granite pediment, and basaltic lava. This might be similar to what would be expected on the moon or Mars.

There is a great deal of spectral information outside the visible range, particularly in the infra-red, that can be used for discrimination among different objects. Reference (41) gives a detailed discussion of how comparison of the reflectance in the visible region with that in the infra-red region up to $900\text{ m}\mu$ can be very useful in providing discrimination among different objects.

Reference (42) gives spectral reflectance measurements for $0.3\text{ m}\mu$ to $3\text{ m}\mu$ measured from the air of snow, water, typical Florida greenery (pine trees, groves, and open fields). References (43) and (44) contain extensive measurements of infra-red spectra of various types of terrain and sky in the vicinity of Pikes Peak. The data covers two infra-red regions $1\text{ m}\mu$ to $7\text{ m}\mu$ and $2.5\text{ m}\mu$ to $20\text{ m}\mu$. Reference (45) gives similar infra-red spectra of the sky and reference (46) of the terrain in the vicinity of White Sands, the Rocky Mountain area in Colorado, and Cape Canaveral in Florida. Reference (47) gives infra-red spectral radiance measurements from $1.5\text{ m}\mu$ to $6\text{ m}\mu$ of various objects such as moon, sky, concrete wall, snow, etc.

The ozone layer begins to attenuate the ultra-violet below $320\text{ m}\mu$ and forms an almost complete shield for radiations below $290\text{ m}\mu$ as shown in reference (48). This is indeed fortunate, because high radiations below that region would severely damage living cells. Because of the lack of natural ultra-violet radiation on earth, we do not have data of reflectivity of terrain below $300\text{ m}\mu$, but there is data available in the near ultra-violet above that region. Reference (49) gives spectral recordings from the sun and sky radiations from $297.5\text{ m}\mu$ to $370\text{ m}\mu$, and Reference (42) gives measurements of spectral reflectance of terrain down to $330\text{ m}\mu$.

Conclusions from Survey It is apparent from the data that there is a great deal of spectral information in the infra-red that would be very useful for discrimination purposes. In outer space where ultra-violet radiation is high, there also should be important information in the ultra-violet.

One way to sense this information in the infra-red and ultra-violet is to make spectrum analyses, but this is much too slow and

cumbersome for many applications. Another approach is to photograph the scene through different cameras and use multi-colored projections, to form a modified picture similar to a normal color print, as is described in reference (41). However, the ideal approach would appear to be to construct a camera mechanism that operates in the same manner as the eye (as prescribed in the Spectral Scanning theory) in which adaptation is performed in terms of spectra. Such a mechanism would be able to achieve the high resolution in the infra-red region necessary for fine discrimination.

Thus our study has indicated the need in space exploration for more effective spectral sensing devices operating in the infra-red and probably ultra-violet regions.

SECTION 4

EXTENSION OF YILMAZ THEORY

4.1 SUMMARY OF WORK ON YILMAZ THEORY

The Yilmaz theory of color perception^{3,4} provided a basic theoretical frame of reference with which to approach the visual adaptation process. The general principle that Yilmaz set forth is as follows:

In order for object colors to remain essentially invariant with changes of illumination, the changes of color sensation with changes of illumination must follow an approximately Relativistic transformation in perceptual coordinates.

In order to apply this principle to yield quantitative results, research was performed, based on theoretical analysis and on a study of experimental color matching data under different states of adaptation.

Our empirical analysis enabled us to derive a simple equation defining the achromatic adaptation process, which was consistent with previous empirical findings of experimenters in the field of color vision. Our study of experimental color matching data led us to the conclusion that we should consider chromatic adaptation more in terms of spectra, a conclusion that was reached by Alan Calhamer of the Applied Research Laboratory. This reinforced the Spectral Scanning Theory and led to the postulate that each cone acts as a spectrum analyzer, and the retina performs visual adaptation in terms of spectral information. By combining this principle with the equation derived for achromatic adaptation a simple model of chromatic adaptation resulted.

Section 4.2 discusses the theoretical work extending the Yilmaz theory to derive the transformation equation for achromatic adaptation. Section 4.3 discusses the study of the color matching experimental data, which led to the concept that chromatic adaptation may be performed in terms of spectra. A discussion of how the achromatic transformation of the Yilmaz theory is incorporated within the Spectral Scanning theory to produce chromatic adaptation is given in Appendix C.

The Yilmaz theory leads to the conclusion that a signal proportional to the difference between the instantaneous luminosity and the time

average luminosity is generated in the receptors in the optical detection process. Such an effect could occur if the photopigment regeneration process in the receptors generates a negative current that opposes the current generated in the photopigment bleaching process.* A negative current due to regeneration would produce shot noise that would raise the visual threshold. Therefore, the concept of a negative current due to regeneration can be evaluated by calculating the shot noise for that current and relating it to visual threshold. Reference (10) performs such a calculation and shows that the calculated value of a visual threshold based on this assumption is reasonably consistent with experimental data.

4.2 THEORETICAL WORK EXTENDING YILMAZ THEORY

The Relativistic transformation that Yilmaz predicts behaves in terms of perceptual coordinates, but unfortunately, we have no clear means of defining perceptual coordinates. In his preliminary experiments,^{3,4} Yilmaz used Munsell chips and defined his perceptual coordinates in terms of Munsell coordinates. To achieve a more precise formulation he sought a means of transforming spectral response.

By perceptual coordinates, we mean the coordinates of the color sensations experienced in viewing a scene. In order to work in perceptual coordinates, we first must set up a standard of color sensation. The nearest thing we now have for a perceptual color standard is the Munsell system of color samples. This could be used as a basis for a color perception standard by constructing a viewing box in which individual Munsell samples are observed under a standardized illuminant, as small chips against a standardized background. Such a viewing box would define the coordinates of a color sensation in a quantitative manner. To determine the coordinates of a sample color sensation in

* Light falling on a molecule of the photosensitive material in the receptors (called the photopigment) initiates a chemical change which results in the bleaching of the molecule. Bleached molecules revert back to the original state at a rate proportional to the concentration of bleached molecules.

a given experimental situation, that situation could be viewed by one eye and the standardized viewing box viewed by the other. By changing the Munsell chips in the viewing box until a binocular match is made with the sample, one can determine which Munsell chip in the standardized viewing condition matches the sample. The perceptual coordinates of the sample then must be equal to the perceptual coordinates of the Munsell chip.

Munsell chips are arranged in an orderly manner perceptually and are specified quantitatively by the parameters, hue, chroma, and value. These parameters do not define the coordinates of our perceptual coordinate system, but there is a direct one-to-one mapping between the Munsell parameters under standardized viewing conditions and perceptual coordinates. An important part of our research is to determine what this mapping is.

Another problem with using Munsell chips to form a perceptual standard is that under usual viewing conditions the chips do not evoke the maximum possible color sensations. Higher sensations can be evoked by varying the background to achieve greater contrast. For the maximum saturation sensations, the samples may have to be replaced by active lights. Such techniques will be required to extend the Munsell color perception standard to achieve the maximum chromatic sensations as well as the maximum black and white sensations.

Thus we have shown that it is possible to set up a standard for defining color sensations in a quantitative manner in perceptual coordinates. Yilmaz's theory predicts that if we are able to make the appropriate mapping from Munsell coordinates to perceptual coordinates, color transformations with respect to the perceptual coordinates should be approximately relativistic.

What should be the general shape of our perceptual coordinates? The Munsell coordinates are cylindrical. Yilmaz proposed a perceptual coordinate system that was conical. However his coordinate system has the disadvantage that it did not properly account for the effect of changes in intensity of illumination. Yilmaz dealt with this factor by normalizing his signals.

Further study has indicated that a spherical coordinate system is much more reasonable for perceptual color space. Figure 4-1 shows the spherical coordinate system. The center of the sphere represents grey. On the surface of the sphere are points representing the maximum color sensations achievable. These represent the most saturated red, green, yellow and blue sensations around the equator of the sphere and the strongest possible white and black sensations at the poles. It is postulated that when our perceptual space is appropriately defined, all color sensations will fall within a sphere, and the radius of the sphere will define the maximum possible color sensation in any direction.

Now let us consider what we mean by color transformations in color perceptual coordinates. Assume that we make four experiments, as indicated in Figure 4-2, in which we match the color sensation of a given spot of light, seen against a given background light, with our viewing box which contains the perceptual color standard. The four experiments will determine the coordinates of the color sensations achieved under the following conditions:

- (1) A spot of light sample (S) against a background of light (A)
- (2) A spot of light (B) against a background of light (A)
- (3) A spot of light sample (S) against a background of light (B)
- (4) A spot of light (A) against a background of light (B)

These experiments will give color sensation vectors designated as S_A , B_A , S_B , A_B respectively, where the subscript denotes the background light.

Figure 4-2a shows the vectors S_A and B_A , which indicate the color sensations produced by lights (S) and (B) against a background of light (A). Figure 4-2b shows the vectors S_B and A_B which indicate the color sensations produced by lights (S) and (A) against a background of light (B). The problem of color transformation is to determine the vectors S_B and A_B when we know the vectors S_A and B_A . The Yilmaz theory postulates that S_B and A_B are related by a relativistic transformation to S_A and B_A .

To obtain our relativistic transformation, let us consider that the radius of the perceptual color sphere is analogous to the speed

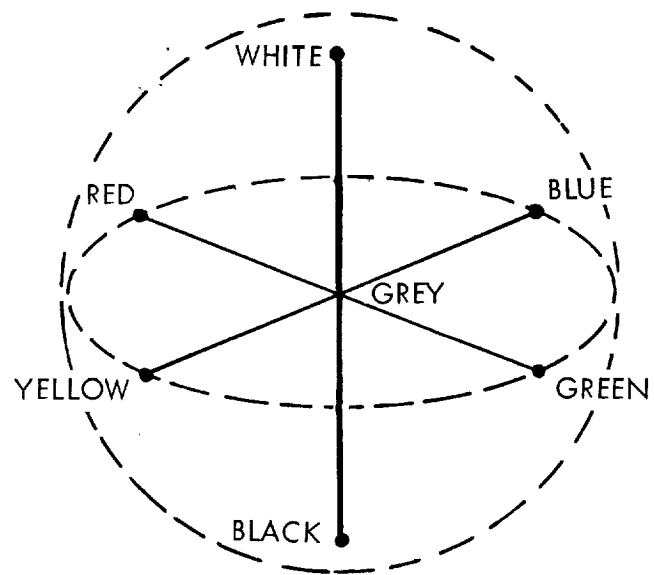
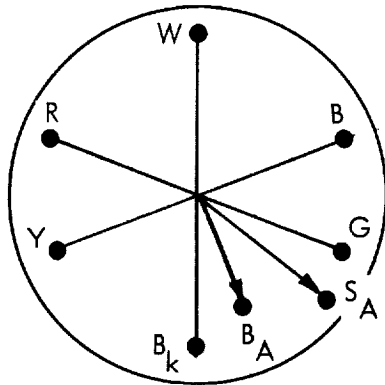
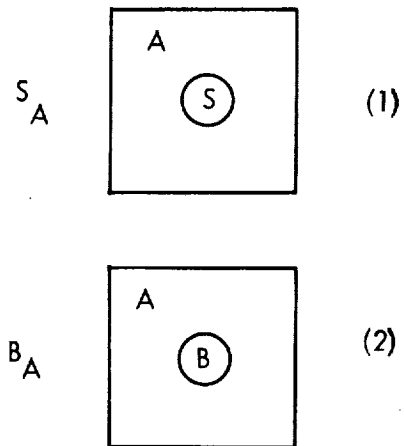


Figure 4-1. Perceptual Color Coordinates

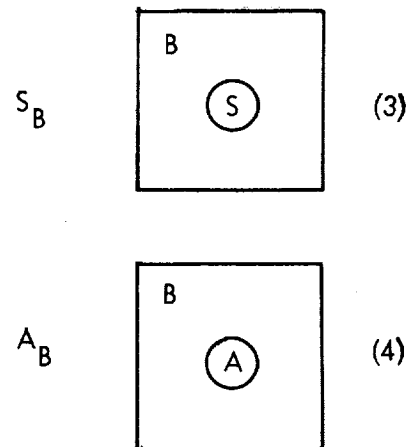
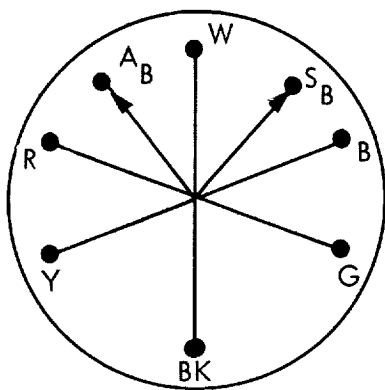
PERCEPTUAL
COLOR
COORDINATES



TEST
IMAGE



(a) CONDITION WITH (A) AS BACKGROUND LIGHT



(b) CCNDITION WITH (B) AS BACKGROUND LIGHT

Figure 4-2. Example Defining Color Transformation in Perceptual Coordinates

of light and that a vector from the center to any point in the sphere is analogous to a velocity vector in the particular coordinate system. A change of background illumination is analogous to a change of the velocity of a coordinate system. By applying this analogy to the Lorentz transformation of Special Relativity, a Relativistic transformation for our color space can be derived.

Before writing the equations for the Relativistic color transformation, let us examine its general effect. Assume for simplicity that the light sensations vectors B_A and S_A lie in a vertical plane in the perceptual coordinates, say, in the green-red/white-black plane, as shown in Figure 4-3. The solid axes and circle define the perceptual color space as seen with light (A) as the background and the dashed axes and circle defines the perceptual color space as seen with light (B) as the background. Changing the background light from (A) to (B) has the effect of moving the origin from 0 to B_A and distorting the space from the solid circle to the dashed circle. The effect of the distortion is to move the point S_A of the sample to a different point S_B , in accordance with a Relativistic transformation.

Figure 4-4 shows the equations for the Relativistic transformation expressed in a convenient coordinate system. The parameter σ defines the radius vector to a point. For convenience the maximum radius of the perceptual sphere is normalized to unity. Points S_A and B_A represent the color sensations of lights (S) and (B) seen against background (A). The distances of these points S_A and B_A from the origin for the coordinate system of light (A) are represented by σ_{SA} and σ_{BA} , respectively. To determine the coordinates of light sample (S) against background (B), which represents the vector S_B , it is convenient to use the coordinate system X-Y shown in Figure 4-4. The X-axis lies along the vector $O-B_A$ and the Y-axis is perpendicular to the X-axis at the point B_A , such that point S_A lies in the plane of the X and Y axes. The coordinates of the vector S_B (i.e., the color of light sample (S) against a background of light (B) in the X-Y coordinate frame are as follows:

$$Y_{SB} = \frac{\sqrt{1 - \sigma_{BA}^2} \sigma_{SA} \sin \phi}{1 - \sigma_{BA} \sigma_{SA} \cos \phi} \quad (4-1)$$

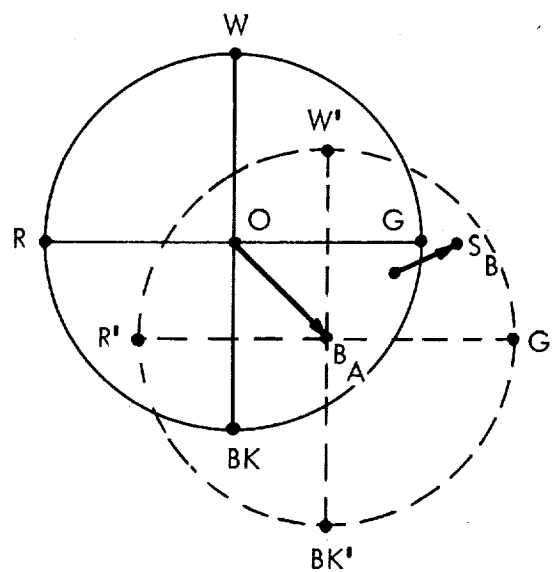


Figure 4-3. Simple View of Relativistic Transformation in Perceptual Coordinates

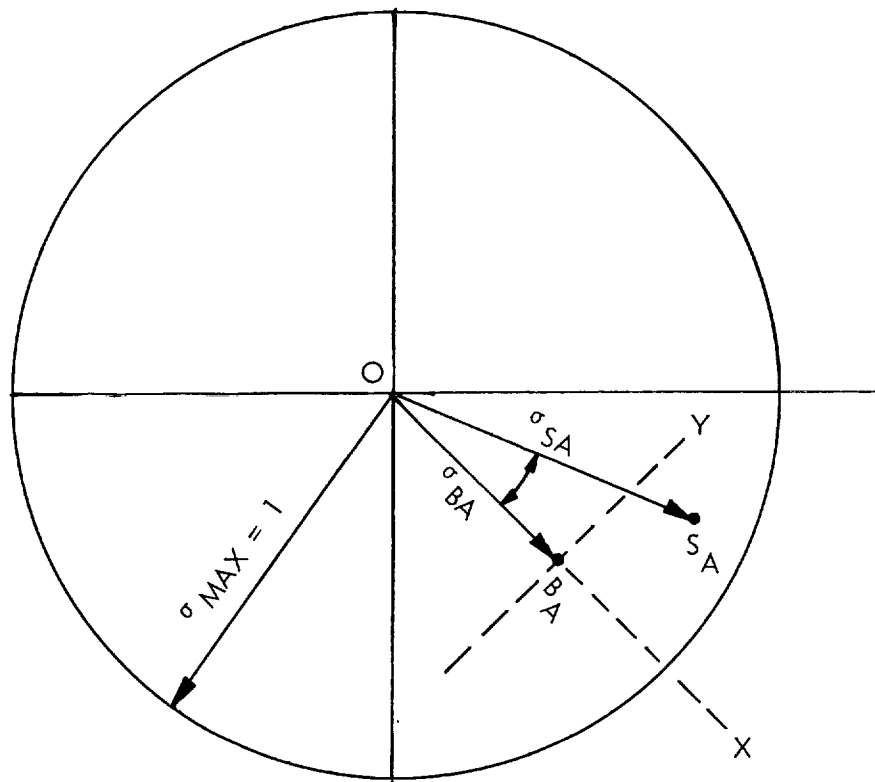


Figure 4-4. Definition of Parameters in Equation for Relativistic Color Transformation

$$x_{SB} = \frac{\sigma_{SA} \cos \phi - \sigma_{BA}}{1 - \sigma_{BA} \sigma_{SA} \cos \phi} \quad (4-2)$$

where ϕ is the angle between the vectors $O-B_A$ and $O-S_A$.

Equations (4-1) and (4-2) give the coordinates of the color samples (S) against background (B) in terms of axes X-Y which are rotated with respect to the color axes white-black, green-red, and blue-yellow. From the geometry of the color system one can easily determine the relative orientation between the X-Y axes and the color axes, and by appropriate rotation of coordinates one can determine the color coordinates of sample (S) against background (B). Thus Eqs. (4-1) and (4-2) are sufficient to describe the Relativistic color transformations.

As a first step in applying the Relativistic transformation, let us consider two lights (B) and (S) that appear achromatic against a background of light (A), and so lie along the black-white axis. For this condition ϕ is zero, y_{SB} is zero, and x_{SB} becomes σ_{SB} . Our Relativistic transformations of Eqs. (4-1) and (4-2) reduce to the single equation

$$\sigma_{SB} = \frac{\sigma_{SA} - \sigma_{BA}}{1 - \sigma_{SA} \sigma_{BA}} \quad (4-3)$$

Let us make the following postulate for lights that appear achromatic with respect to one another.

If the luminosity ratio L_S/L_B of light (S) to light (B) is equal to the luminosity ratio L_B/L_A of light (B) to light (A), then light (S) will have the same appearance against background (B) as light (B) has against background (A).

If we express this mathematically we have the following. If

$$\frac{L_S}{L_B} = \frac{L_B}{L_A} \quad (4-4)$$

then

$$\sigma_{SB} = \sigma_{BA} \quad (4-5)$$

since σ_{SB} and σ_{BA} define, respectively, the color sensations of sample (S) against background (B) and light (B) against background (A). It can be shown that the solution of Eqs. (4-3), (4-4), and (4-5) is of the form

$$\sigma_{12} = \tanh \text{Log}_a (L_1/L_2) = \frac{(L_1/L_2)^\beta - 1}{(L_1/L_2)^\beta + 1} = \frac{L_1^\beta - L_2^\beta}{L_1^\beta + L_2^\beta} \quad (4-6)$$

where α and β are unknown constants.

Equation (4-6) gives a theoretical relation between a perceptual coordinate σ_{12} and the corresponding luminosity ratio (L_1/L_2) . It is equivalent to a relation between Munsell value and reflectance. Thus it provides a theoretical basis for defining the relationship between value and reflectance, which is a significant result.

The quantity σ varies from -1 to +1 while Munsell value V varies from 0 to 10. Thus the relationship between value V and sensation σ could be taken as

$$V = 5(1 + \sigma) \quad (4-7)$$

Combining Eqs. (4-6) and (4-7) gives

$$V = \frac{10 L_1^\beta}{L_1^\beta + L_2^\beta} \quad (4-8)$$

Adams and Cobb²² derived in 1922 from empirical reasoning the following relationship between Munsell value and luminosity

$$V = \frac{10 L_1}{L_1 + L_2} \quad (4-9)$$

This relationship has been shown by Judd* to give a good description of the visual adaptation process. Thus, we may assume that β is unity. Our equation for sensation becomes

$$\sigma_{12} = \frac{L_1 - L_2}{L_1 + L_2} \quad (4-10)$$

Thus, we have derived a very simple expression for the relationship between luminosity and sensation which satisfies the Lorentz transformation in accordance with the Yilmaz theory of color transformation and also agrees well with experimental data, as was shown by Adams and Cobb and by Judd. This expression leads to the conclusion that the optical detection mechanism may act electrically as a simple bridge circuit, as is described in Reference 12, page 54.

Now let us generalize this result to include chromatic adaptation. The Spectral Scanning theory postulates that each cone of the eye acts as a spectrum analyzer. If these spectrum analyzers adapt so that at each frequency the relation of Eq. (4-10) is satisfied, the system will achieve a relativistic transformation with respect to chromaticity changes as well as intensity changes. Thus, by combining the Biernson Spectral Scanning theory and the Yilmaz color perception theory, a simple color transformation model results, which is described in Appendix C and reference (12).

4.3 STUDY OF ADAPTATION COLOR-MATCHING DATA

4.3.1 Problem of Color Transformation

An important phenomenon of color vision is the near invariance of object colors under changes of illumination. It is reasonable to assume that the color of the illuminant is approximately sensed in the visual system by taking an average (probably a weighted average of some sort) of the received light over the visual field. When the illuminant

* Reference 21, page 226.

is changed, the adaptation of the eye to this average restores the object color more or less to what it was under the original illuminant.

The simple transformation that would satisfy this requirement is a linear shift of the achromatic point in color space with adaptation. Assume that the perceived hue is represented by the direction and perceived saturation by the length of a vector drawn from the point in color space representing the illuminant to the point representing the spectrum of the light from the object. The invariance of object color under a change of illuminant would then require only that matching colors under two illuminants be related by the same vector as the illuminants themselves.

This condition is illustrated in Figure 4-5. Points (Ill.1) and (Ill.2) represent the points in color space corresponding to the spectra of illuminant 1 and illuminant 2. Points A_1, B_1 and C_1 represent the spectra observed under illuminant 1 which match, respectively, the spectra observed under illuminant 2 corresponding to points A_2, B_2 , and C_2 . According to our simple transformation, the vectors from points A_1, B_1 and C_1 to points A_2, B_2 and C_2 respectively, are the same as the vector from (Ill.1) to (Ill.2). In this example, equal brightness is assumed for the lights. A simple linear transformation approximately of this form was assumed by Judd in developing approximate empirical rules for predicting the perceived colors under different illuminants.¹⁹

The simple transformation illustrated in Figure 4-5 runs into serious difficulties when we consider the boundaries of the color space. With such a transformation a color of high saturation would shift outside the diagram. Since this does not occur, Yilmaz^{3,4} postulates that colors of maximum saturation must transform into colors of maximum saturation. This means that boundary points on the color space map into boundary points. This would require a contraction of the vector shifts between perceived colors in the direction of the boundary, as we shift the illuminant toward the boundary, in order to maintain a full circle of hues around the illuminant. Yilmaz postulated the Lorentz contraction of the Theory of Relativity as a transformation that would have this property.

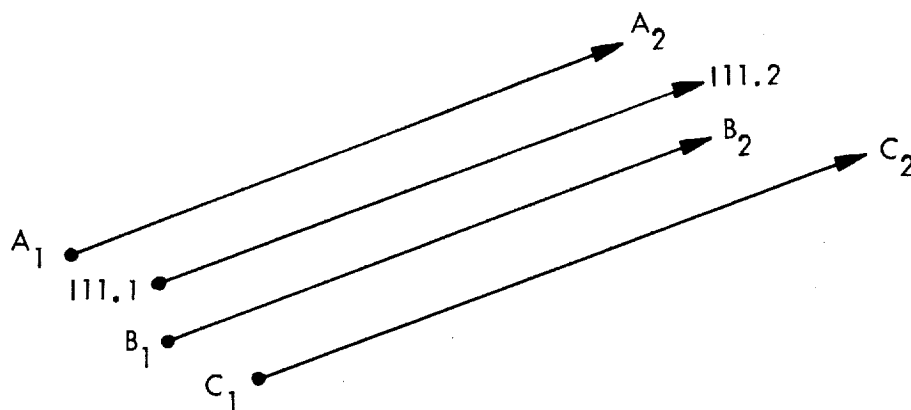


Figure 4-5. First-Order Shift (Schematic)

4.3.2 Investigation of B.E.N. Data

To determine what sort of contraction, if any, takes place in chromatic transformation, we have examined data taken by Burnham, Evans, and Newhall,²⁰ and supplied to us by Eastman Kodak Company. This will hereinafter be referred to as the B.E.N. data.

In the first session of the B.E.N. experiment, the observer had both eyes adapted to CIE standard illuminant C. He viewed twelve different Munsell chips with one eye. He activated equipment so as to present a variable mixture of light to his other eye. When he announced a match, the tristimulus values, X, Y, Z, of the mixture were recorded. In a second session, the first eye was again adapted to illuminant C; the second eye was adapted to CIE standard illuminant A and the procedure repeated. In a third session, the second eye was adapted to a green illuminant which was given the name, illuminant G, and the procedure was repeated.

Diagrams of averaged data, in trichromatic coordinates x and y appear in the B.E.N. article, where $x = X/(X + Y + Z)$ and $y = Y/(X + Y + Z)$. If the x , y values of the illuminants, also given in the article, are added to the diagrams it becomes apparent that the shifts in coordinates of perceived matches under changes in illuminant are approximately in the same direction and of the same magnitude as the shift in the illuminants. This approximation is the same effect as shown in Figure 4-5 and will be called the first order effect. The deviation of the actual shift from this approximation will be called the second order effect.

If a contraction is present, causing a full color world to remain as the illuminant moves toward the edge of the diagram, this contraction must appear as a deviation from the first order effect. To look for this deviation we figuratively prepare two x , y diagrams, one giving the location of illuminant C and the twelve color matches under that illuminant; the other showing illuminant A and the color matches under that illuminant. We superimpose the diagrams, translated so that the illuminants coincide, the parallel sides of the two diagrams remaining parallel. This removes the first order effect for any pair of points

representing matches with the same color. The remaining shift is called the second order effect.

Diagrams of the second-order shift have been studied, covering shifts from Illuminant C to A, C to G, and A to G. The shifts for three B.E.N. observers were studied in detail, but those for the observer 4 were eliminated because his results varied greatly on repetitions of the same match, and his second-order shifts were very erratic.

Figures 4-6, 4-7, and 4-8 show the second-order shifts on the CIE chromaticity diagram for observers 1, 2, and 3, as the illuminant changes from C to A. The lines labeled $z = 0$ correspond approximately to the edge of the chromaticity diagram in this region. These are the lines for $x + y = 1$.

Figure 4-6 shows that there is a definite second-order shift away from the edge of the diagram for Observer 1. Figure 4-7 shows a similar effect for observer 2, but not quite so pronounced. Figure 4-8 shows the shifts for observer 3, which shift in both directions.

Figure 4-9 shows the second-order shifts of Observer 1 in changing from illuminant C to G. Here again there is some evidence of a shift away from the edge but it is not very pronounced.

The most important conclusion to be derived from this data is the great variation of the second-order shifts from one observer to the next. These variations correspond to large perceptual changes in color sensation, and so cannot be attributed to random variations in color matching. The implications of these variations will be discussed later.

There seems to be a very definite indication of second-order shifts away from the edge in the data. However, the erratic variation from observer to observer tends to obscure this effect and make it difficult to fit a quantitative model to the data.

One of the limitations of the B.E.N. experiment is that the colors used for matching were of relatively low saturation. If

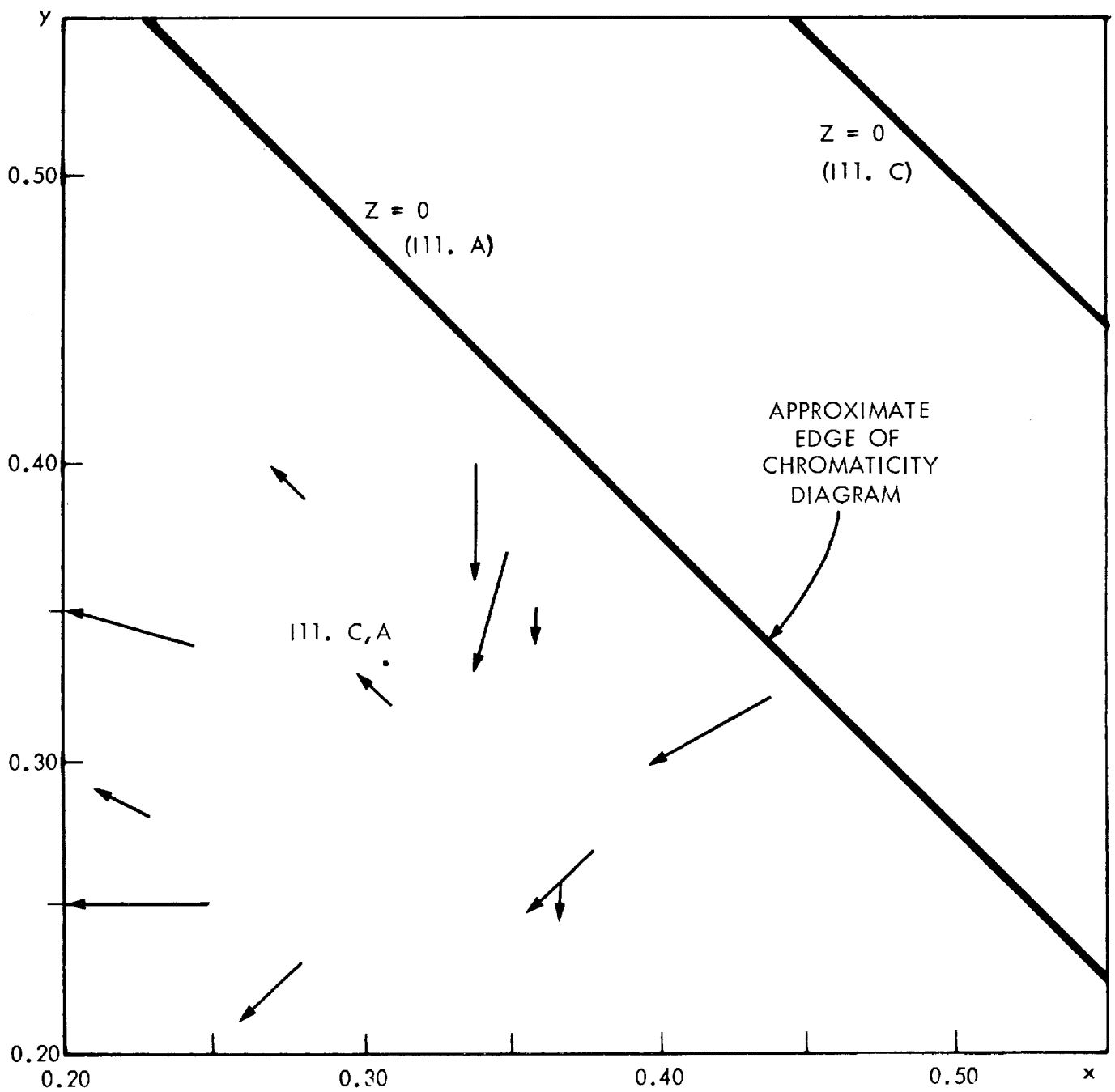


Figure 4-6. Second-Order Shifts of Trichromatic Coefficients in Changing from Illumination C to A. (Observer 1, B.E.N. Data.)

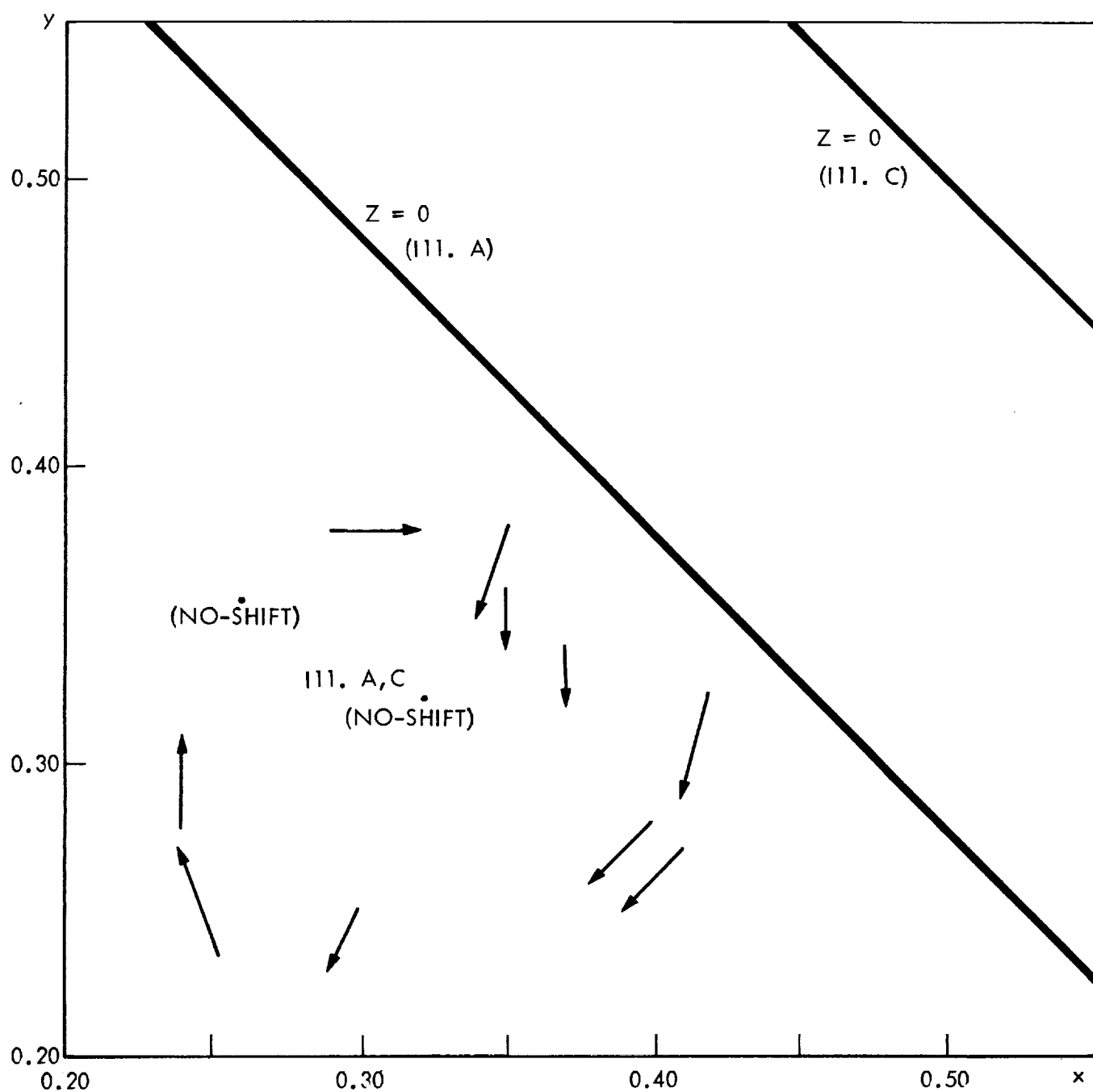


Figure 4-7. Second-Order Shifts of Trichromatic Coefficients in Changing from Illumination C to A. (Observer 2, B.E.N. Data)

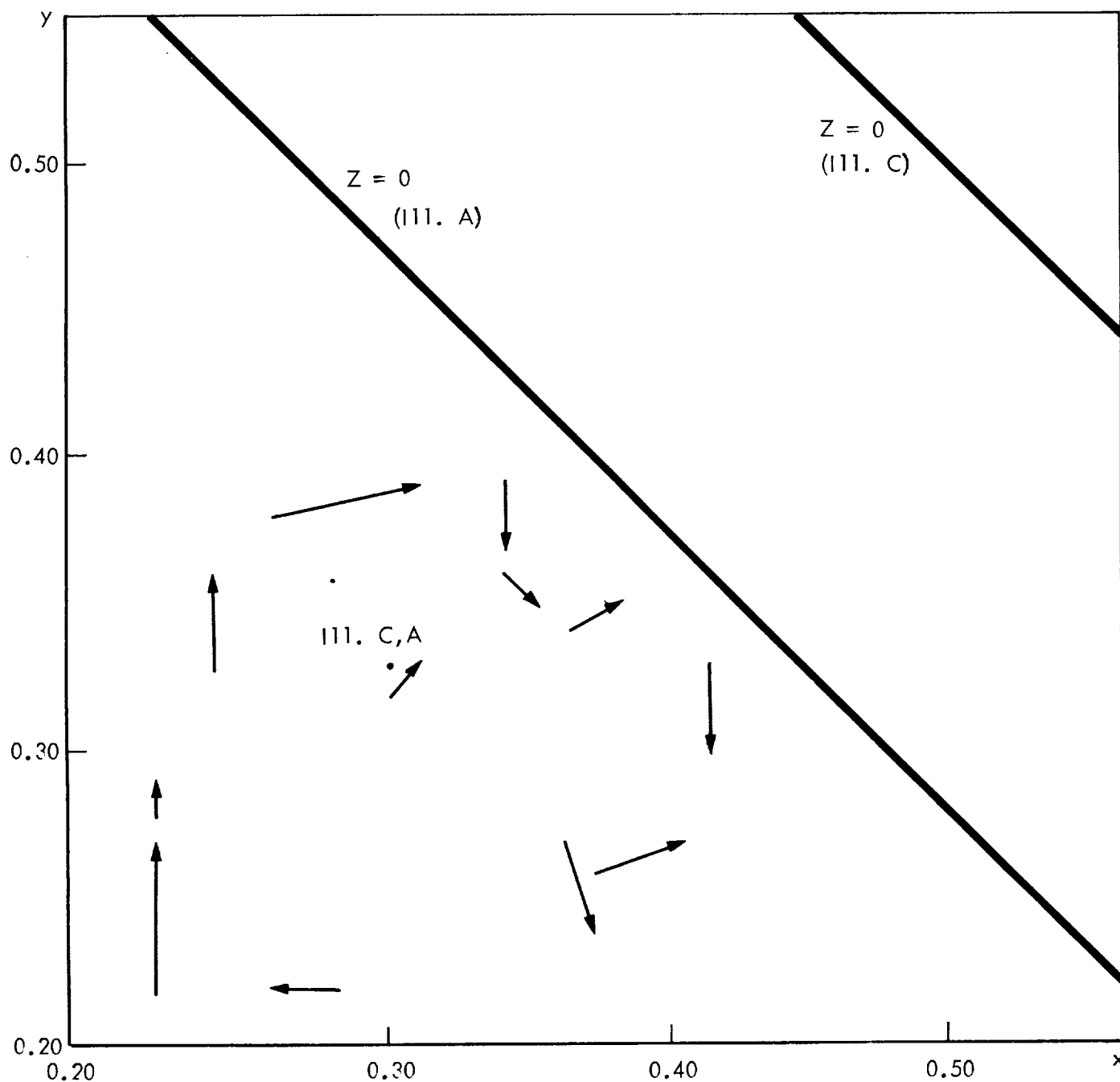


Figure 4-8. Second-Order Shifts of Trichromatic Coefficients in Changing from Illumination C to A. (Observer 3, B.E.N. Data)

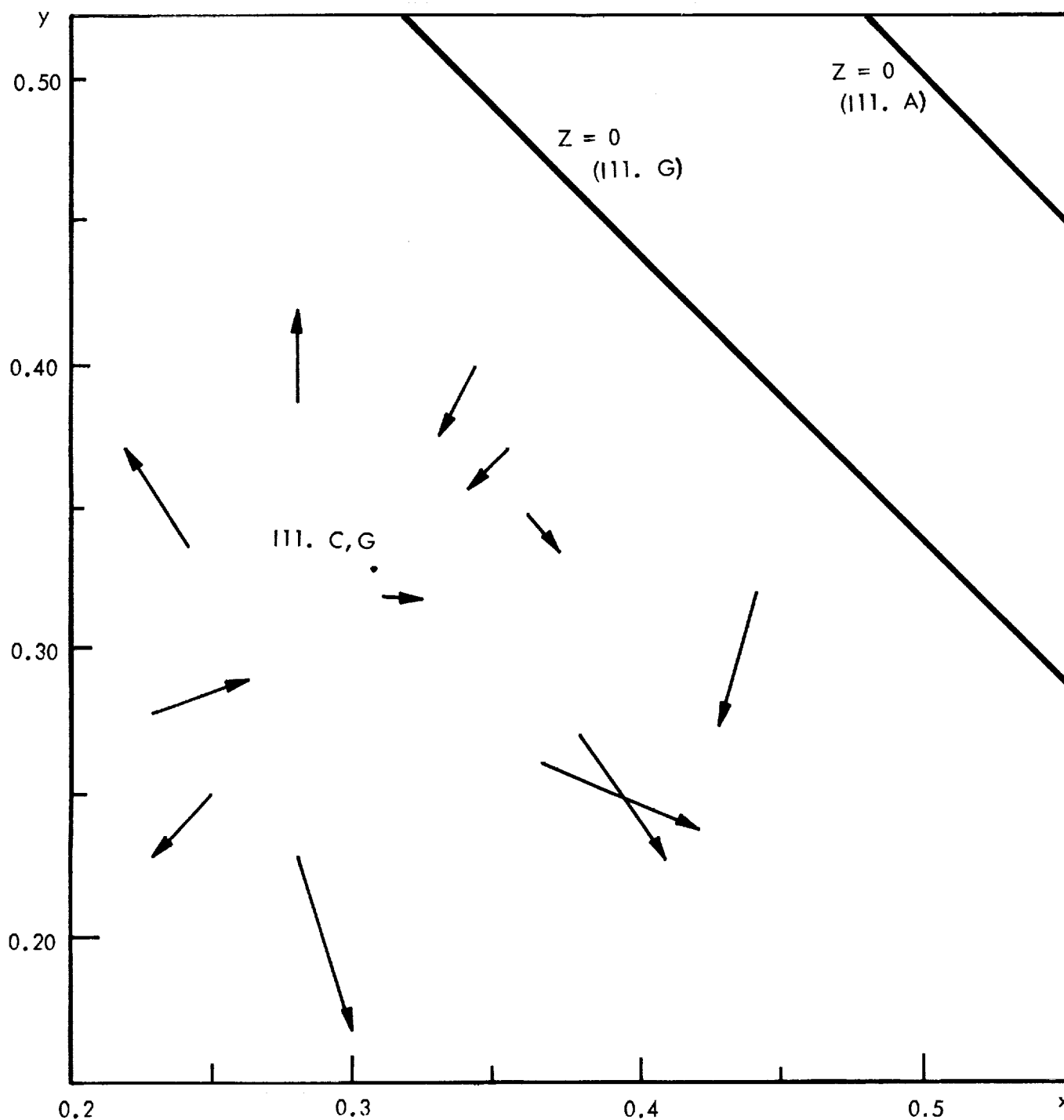


Figure 4-9. Second-Order Shifts of Trichromatic Coefficients in Changing from Illumination C to G. (Observer 1, B.E.N. Data)

more highly saturated samples had been employed, the shift away from the edge might have been more pronounced, relative to the erratic shifts.

4.3.3 Choice of Color Coordinate System

Among the problems involved in fitting the Lorentz transformation or any other suitable transformation to the data are the proper mapping of color into geometric space and the determination of maximum saturation in the various hues.

Samples of the B.E.N. data were examined in a number of color coordinate systems: C.I.E. chromaticity diagram, Uniform Chromaticity Space (UCS) diagram, Munsell coordinates, and the chromaticity diagram of the Spectral Scanning theory. However, it was found that the erratic variation from observer to observer is so great that a simple qualitative study needed to be made just to achieve an overall picture. We therefore chose the convenient CIE diagram because the data is available in those coordinates.

The trichromatic diagram has the advantage of being very commonly used. Data is commonly in such form that it can be put on one of these diagrams very quickly, and familiarity with the diagram makes it easier to interpret. On the other hand, the choice of primaries was arbitrary and is not related to any physical interpretation of color vision, hence simplifications arising from simple physical behavior are likely to be obscured. Brightness information is lost due to normalization.

The weakness in the trichromatic diagrams suggest that a three-space employing tristimulus values should be explored. In such a space, tristimulus value Y is precisely a measure of luminosity. X and Z, while arbitrary in concept, are the sole bearers of hue information. All of the BEN data is in X, Y, Z as well as in the trichromatic coefficients x, y. In particular, inasmuch as Yilmaz postulates that transformations due to adaptation may cause a tilting of the achromatic axis in hue, saturation, and brightness space (or, loosely speaking, may cause brightness to change to saturation or vice versa) it is very desirable to retain brightness information.

The Uniform Chromaticity Space is a space derived by transformation of the trichromatic diagram in such a way that equal distances on it correspond roughly to equal numbers of barely discernible hue differences; in other words, distance is roughly a measure of distinguishability. Since distinguishability may be the basic measure employed by the mind when it is first organized to make sense out of its surroundings, it may well be the basis of the best choice of units for a unified approach to many or all of the senses. For qualitative purposes, however, it is sufficient to work in trichromatic values (as in the graphs of the second-order shift,) bearing in mind that the transformation to U.C.S. diagram would amount largely to a contraction of the green region.

The coordinates of the Munsell system have been considered, along with an appropriate brightness axis. These coordinates form a reasonable model of subjective color sensations as reported by a large number of observers. There is some doubt whether they are of a high enough order of accuracy to help us in dealing with the second order effect. In any case, the Lorentz transformation did not fit data plotted in this space.

From the standpoint of theoretical simplicity and unification, the most interesting prospective color space employs the α, β coordinates of Yilmaz or some close equivalent*. For the third axis, "brightness" is the standard, defined by $\log(r/r_0)$ where r is the received luminosity and r_0 is the average received luminosity over the field. Yilmaz simply employed r as his third coordinate.

The use of "brightness", as the third coordinate places the neutral grey point representing the weighted average over the field at $(0,0,0)$ instead of $(0,0,r_0)$. It permits three dimensions symmetrically dealt with in both positive and negative values, positive meaning simply "lighter than the surround," negative meaning "darker than the surround". This approach requires amendment of Yilmaz' assertion,

* For the similarity of curves derived by Yilmaz to other curves, see Reference (4) pp. 135-7.

"brightness is always a positive quantity"^{*} to read, "luminous flux is always a positive quantity". Luminous flux is a physically defined quantity which is the spectral energy distribution of a light sample, times the curve representing the sensitivity of the eye, integrated over an arbitrarily short period of time. Brightness now may be taken to refer only to the psychological sensation of brightness.

4.3.4 Effects of Spectra

We know that natural objects tend to look nearly the same regardless of changes in illuminant. Therefore let us consider how the tristimulus values of natural objects change with variations of illumination. The Handbook-of Colorimetry⁵⁰ presents spectral reflection curves of typical materials of colors red, orange, yellow, green, blue, and purple. These curves were multiplied by the spectra of illuminants A and C and the color mixture curves \bar{x} , \bar{y} , \bar{z} (using tables in the Handbook of Colorimetry,⁵⁰ pp. 38-42, 45-48), and integrated to determine the tristimulus values X, Y, Z, from which we calculate the trichromatic coefficients x and y.

Figure 4-10 shows the second-order shifts of the trichromatic coefficients for the natural objects when the illuminant is changed from C to A. Many of these colors are much more saturated than those used in the B.E.N. experiment. Colors more equivalent to the B.E.N. colors are formed by mixing the natural spectra with equal energy white, which is achieved simply by moving both matches uniformly closer to the point representing the illuminant, as shown in the figure.

If the colors of the natural objects remained invariant with the change in illuminant, the shifts of Figure 4-10 would correspond to the shifts shown in Figures 2 to 4 for the B.E.N. data. Note that in both sets of figures there are shifts away from the edge in the red, orange, and yellow region. In the blue region there are strangely enough vertical shifts in both sets of figures. Thus there are important

^{*}Reference (4) page 128.

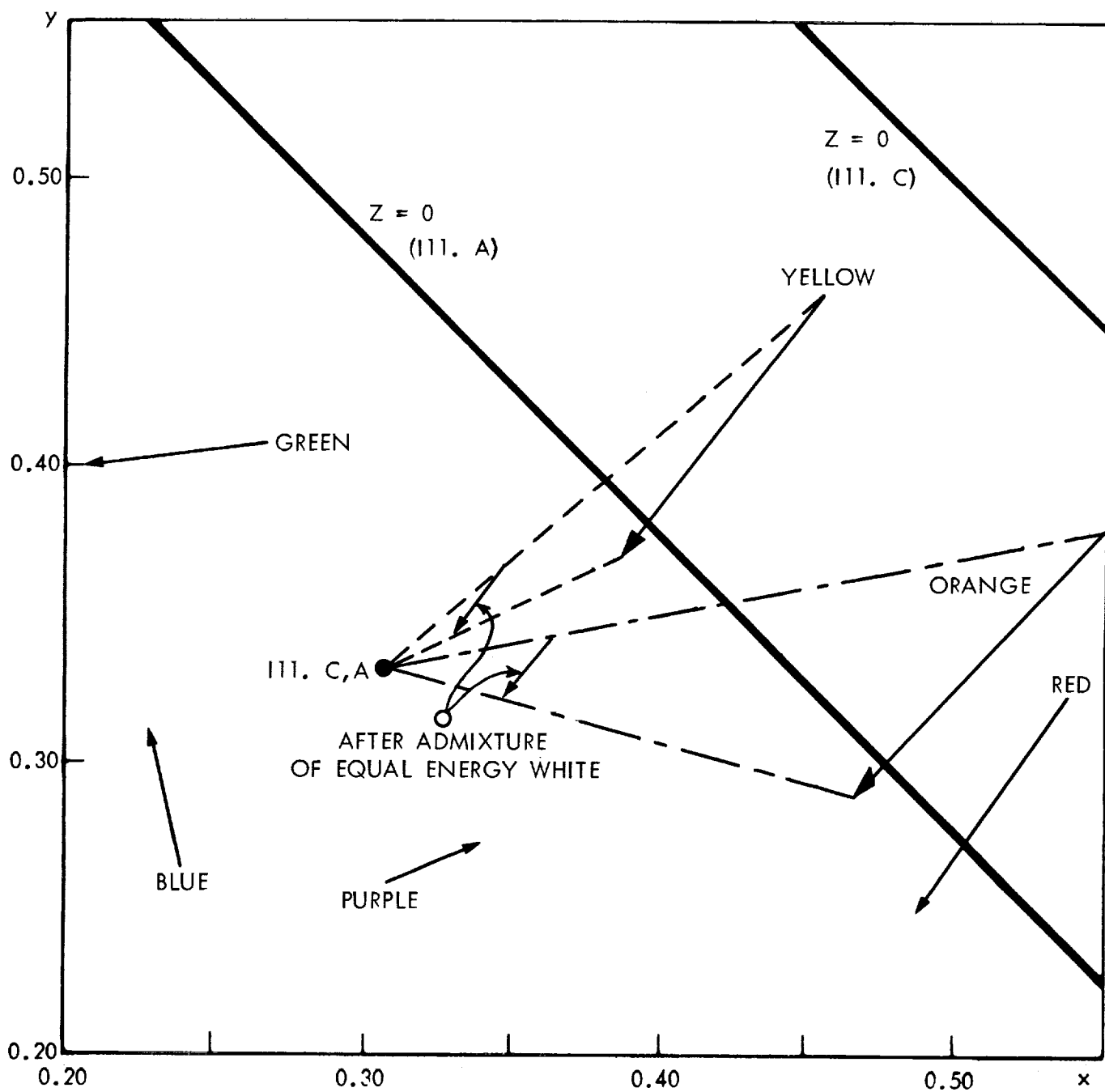


Figure 4-10. Second-Order Shifts in Trichromatic Coefficients of Typical Colored Objects when Illumination Changes from C to A. (Yellow and Orange Lighted by Theoretical Admixture of Equal Energy White)

similarities between the measured second order shifts with chromatic adaptation and those that are required to achieve a constancy of the of the colors of natural objects.

There is an important difficulty in considering color shifts on any diagram based on the standard CIE observer. This is because normal observers differ from one another in color matching by an amount that is relatively large in comparison to some of the second order shifts that are being studied. Consequently if we are to plot shifts we should ideally plot them on a diagram corresponding to the color matching characteristics of the actual observer not an average CIE observer. However to obtain the color matching characteristics of each observer would be extremely difficult. Even this might not be adequate because of the variations of a particular observer with time, size of field, level of illumination, etc.

The real problem, then, is a question of accuracy. Erratic perturbations occur in the data that are due to all these uncontrolled factors. However, one should not assume that these perturbations are small from a perceptual point of view; they are definitely not. This question is similar to the problem of applying tristimulus colorimeters in industry. Judd* has pointed out that a tristimulus colorimeter is quite inadequate for color specification. If two samples have nearly the same spectrum, normal observers will reliably agree in the detection of small differences in spectra. However, if the spectra are matched to three primaries, the variations of the settings of the primaries from one normal observer to the next will be at least five times greater than the variation corresponding to the least detectable difference in spectra.

It is problems such as these that led us to recognize the limitation of tristimulus coordinates for accurate specification of color sensations. We therefore began looking to the spectra themselves for more insight into the problem, as was illustrated in Figure 4-10. This concept led to a strengthening of the Spectral Scanning theory and the postulate that the retina performs visual adaptation in terms of spectra.

* Reference 21, page 123.

SECTION 5

EXTENSION OF SPECTRAL SCANNING THEORY

The initial concept of the Spectral Scanning theory was described in reference (5). On this program the concept was extended to generate a theory consistent with experimental data that was described in reference (11). This work was later revised in reference (12) to clarify the issues involved and included the effects of visual adaptation.

The essential concept of the Spectral Scanning theory is that each cone of the eye acts as a miniature spectrum analyzer. Visual adaptation is performed within the cone in terms of spectral information. This can allow very high accuracy of spectral discrimination to be achieved by means of simple feedback processes. The modified spectral information is then demodulated to form the three-dimensional opponent color signals (white-black, green-red, and blue-yellow) that are sent to the brain.

Appendix B compares the Spectral Scanning theory with classical theories of color vision and Appendix C shows how the Yilmaz theory is incorporated within the Spectral Scanning theory to explain the visual adaptation process.

SECTION 6

EXPERIMENTAL SIMULATION OF VISION

6.1 SUMMARY OF EXPERIMENTAL SIMULATION

One of the tasks on the contract was to simulate normal color vision super color perception, and non-visual region perception. Our studies of the Spectral Scanning theory indicated that scanning and demodulation functions are critical parts of the color vision process, and consequently we concentrated on the simulation of these aspects of vision.

Super color vision represents an extrapolation of the human visual process to machines in which more than three Fourier components of the spectrum are formed.¹ According to the Yilmaz color vision theory,^{1,3,4} as a first approximation the human eye takes three Fourier series components of the spectrum in achieving color vision. In our experimental work on super color vision we simulated a detection mechanism that measures 5 Fourier components of the spectrum.

Non-visual region perception should have great use in space exploration, because there is a great deal of discrimination information outside the visual region, particularly in the infra-red. The eye appears to avoid the infra-red region because infra-red rays generated by heat in the eyeball would add noise to the signal. A difficulty with extending the spectral region to cover the visual and infra-red regions simultaneously, is that the wavelength resolution would be poorer if a simple three-component visual mechanism were employed. However, by employing super color vision, a perception system covering the normal visual range plus the infra-red could have the same discrimination capability as one covering only the normal visual range.

Thus, the combination of super color vision and non-visual region perception would appear to be useful for advanced optical sensing device. In our simulation efforts we have considered the non-visual region simulation to be included within the simulation of super color vision.

Our simulation technique for normal color vision was to prepare masks for an oscilloscope screen having shapes corresponding to our estimate of the spatial energy distributions within the cones for various wavelengths. By an electronic scanning technique, which simulates the scanning process within the cones, this energy distribution data is converted to a modulated waveform, which simulates the modulated signal developed in the cones. The modulated waveform is filtered to form a signal corresponding to the luminosity information and demodulated to form signals corresponding to blue-yellow and green-red information. We compared the resultant color signals with what should be experienced by the white-black, blue-yellow, and green-red sensations at those wavelengths.

To simulate super color vision (and non-visual region perception) masks were prepared corresponding to the energy distribution for a particular wavelength that would be generated in our ideal super color vision detector. These were scanned to produce modulated waveforms, which were then demodulated to form 5 Fourier components corresponding to that wavelength. These components consisted of a constant term, $\cos \phi$, $\sin \phi$, $\cos 2\phi$ and $\sin 2\phi$, where ϕ is the normalized frequency which varies over one cycle. The region from -180 degrees to 0 degrees could correspond to the infra-red range and that from 0 degrees to 180 degrees could correspond to the normal vision range.

6.2 SIMULATION OF NORMAL COLOR VISION

The demodulation principle which is assumed to be performed to generate the blue-yellow and green-red signals is described in reference (12), Section 4. It is assumed that the modulated signal is fed through a highpass filter, to remove the average value, and a phase inverter, to generate two a-c components which are the negative of one another. The blue-yellow demodulator alternately samples the two a-c components every half cycle. The green-red demodulator alternately samples the two a-c components every quarter cycle.

Figures 6-1, 6-2, and 6-3 show the waveforms associated with the blue-yellow and green-red demodulation processes for 9 particular wavelengths. The waveforms shown are those that were calculated in reference (12), and shown in Figure 11 of that report. The corresponding energy distributions were shown in Figure 10 of that report.

The upper two curves of each set in Figures 6-1 to 6-3 are for the blue-yellow demodulation process and the lower two curves for the green-red demodulation process. The approximate square-wave signals represent the demodulated signals. These are filtered to produce the blue-yellow and green-red signals. Ideally these would be exactly square-wave signals, but there is some droop because of the non-ideal character of the demodulator.

The continuous signals in Figures 6-1 to 6-3 show the positive and negative phases of the a-c portion of the modulated waveform. The square-wave output signal for each demodulator is superimposed on the two a-c input signals to show how the sampling is performed. Because of non-ideal characteristics in the demodulation process, the square-wave and corresponding a-c input do not exactly correspond at the sampling instants.

Table 6-1 lists for each wavelength the values of the normalized blue-yellow and green-red signals b and g measured from the experiment, and compares them with the actual values. The actual values were obtained from Table III, page 131, of reference (12).

In the experiment we neglected to record the sign of the output signal, although it was generally found that it behaved as it should. For this reason we cannot be sure of the sign of the signal when g or b is close to zero, and so some measured quantities are indicated with a \pm sign.

6.3 SUPER COLOR VISION

Figures 6-4 and 6-5 show the spatial energy distribution across the detector that must be satisfied in our super color detector for

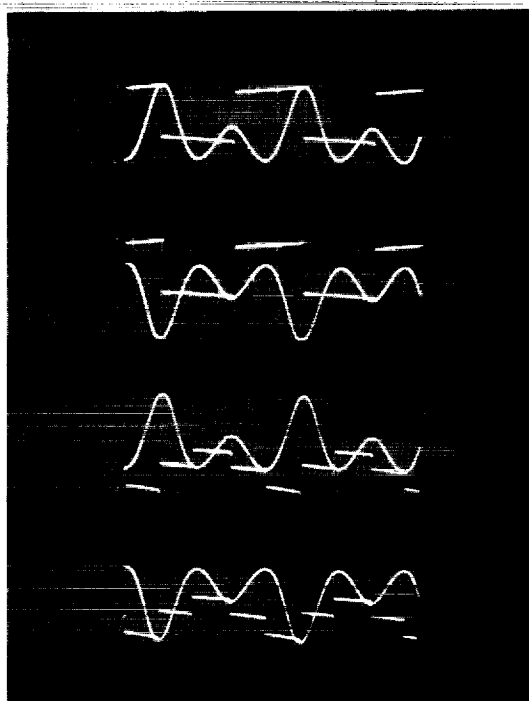
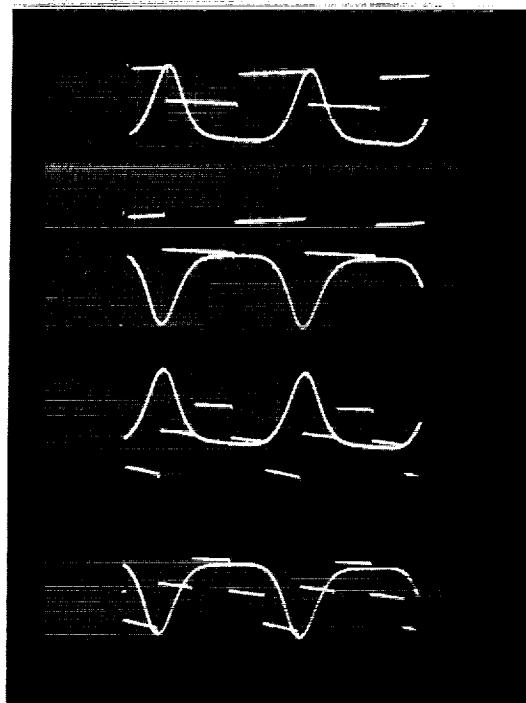
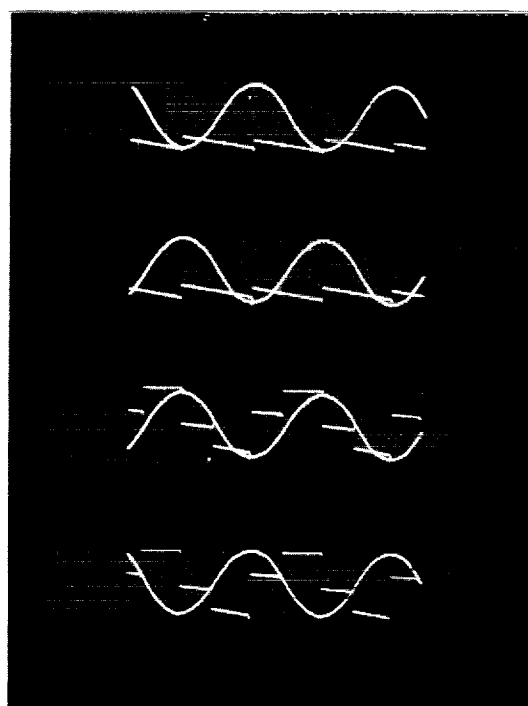
RED (700m μ)ORANGE (590m μ)YELLOW (576 m μ)

Figure 6-1. Waveforms of Demodulated Processes for Theoretical Model of Normal Color Vision at 576 m μ , 590 m μ , and 700 m μ

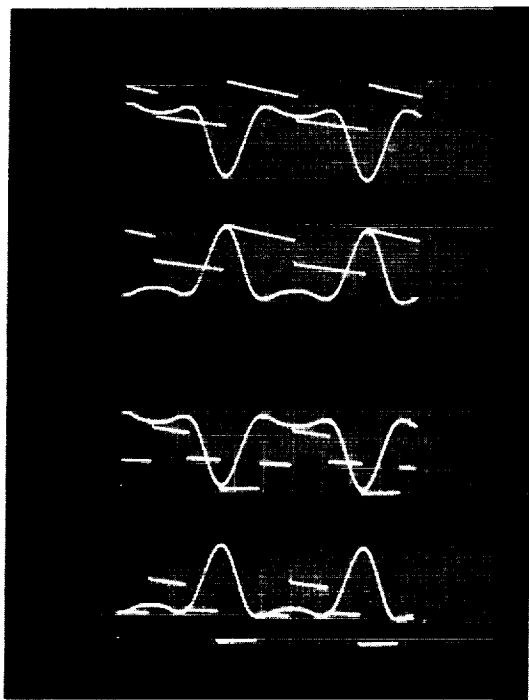
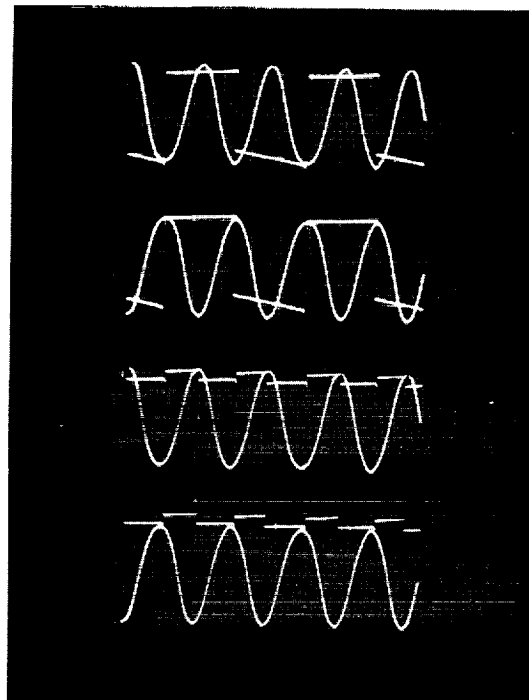
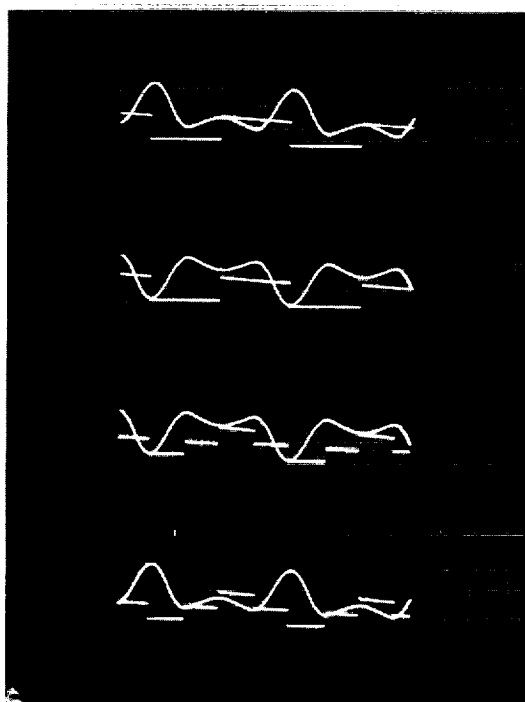
YELLOW GREEN (560 $m\mu$)GREEN (504 $m\mu$)BLUE-GREEN (490 $m\mu$)

Figure 6-2. Waveforms of Demodulated Processes for Theoretical Model of Normal Color Vision at 490 $m\mu$, 504 $m\mu$, and 560 $m\mu$

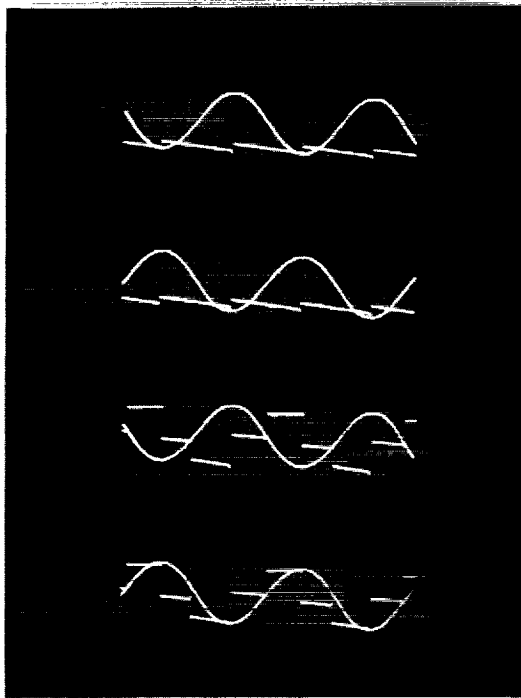
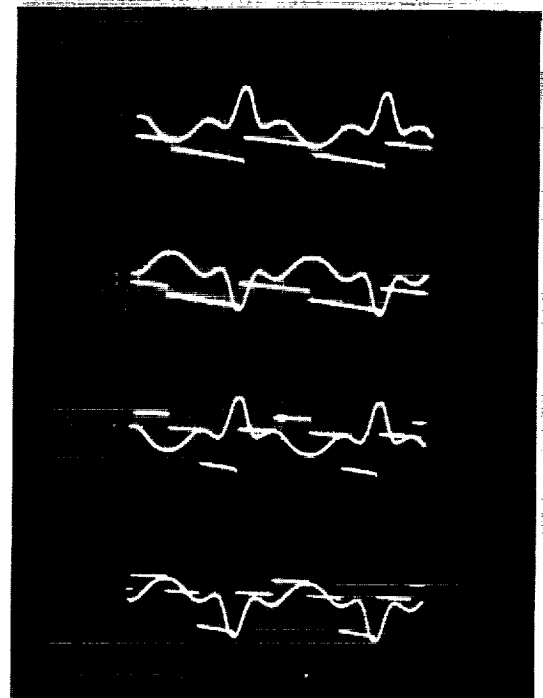
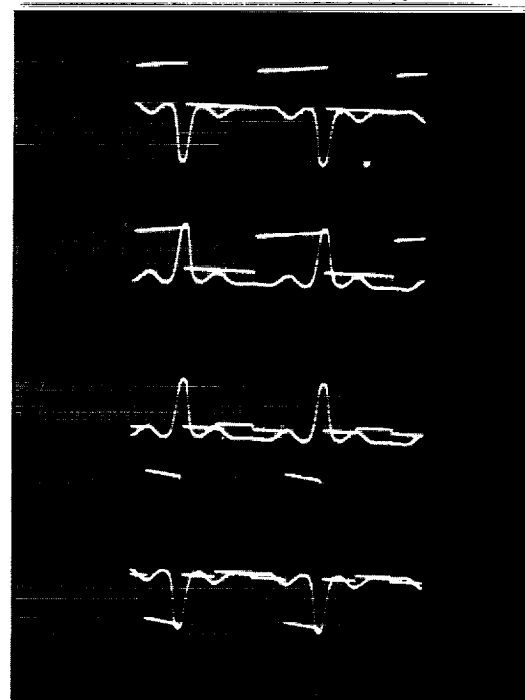
BLUE (477 $m\mu$)BLUE-VIOLET (470 $m\mu$)VIOLET (445 $m\mu$)

Figure 6-3. Waveforms of Demodulated Processes for Theoretical Model of Normal Color Vision at 455 $m\mu$, 470 $m\mu$, and 477 $m\mu$

TABLE 6-1

Wavelength (m μ)	Color	b		g	
		Actual	Measured	Actual	Measured
445	Violet	14.7	11.10	-9.75	-8.0
470	Blue-Violet	5.90	5.12	-1.92	-1.25
477	Blue	3.30	3.64	0	± 0.4
490	Blue-Green	0.92	0.98	1.57	1.68
504	Green	0	± 0.01	1.946	2.08
560	Yellow-Green	-0.595	-0.62	0.786	0.77
576	Yellow	-0.748	-0.78	0	± 0.03
590	Orange	-0.880	-0.84	-0.742	-0.735
700	Red	-1.410	-1.42	-3.59	-3.9

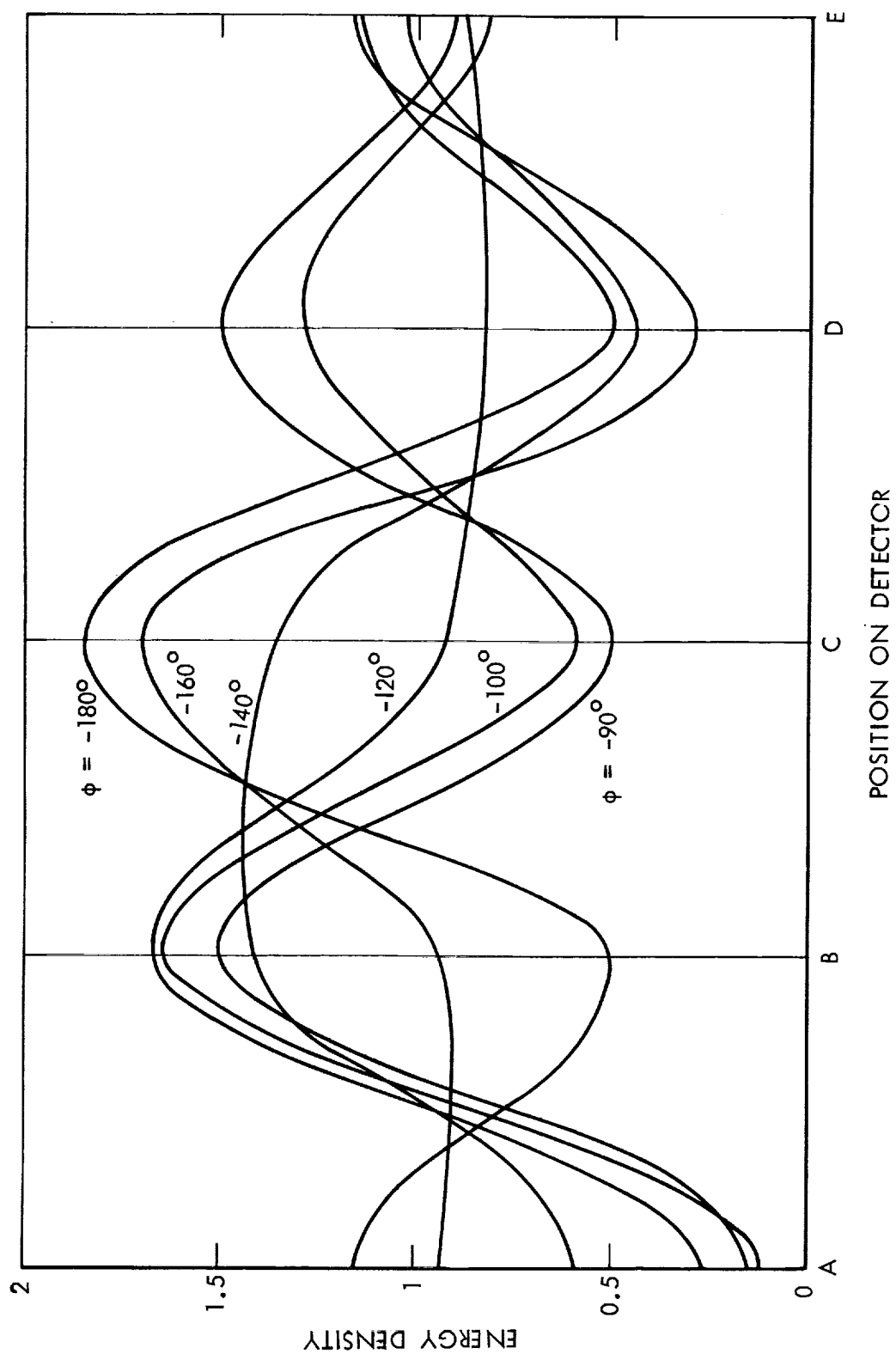


Figure 6-4. Energy Density Plots of Super Color Perception Detector for Values of Normalized Frequency ϕ Between -180° and -90°

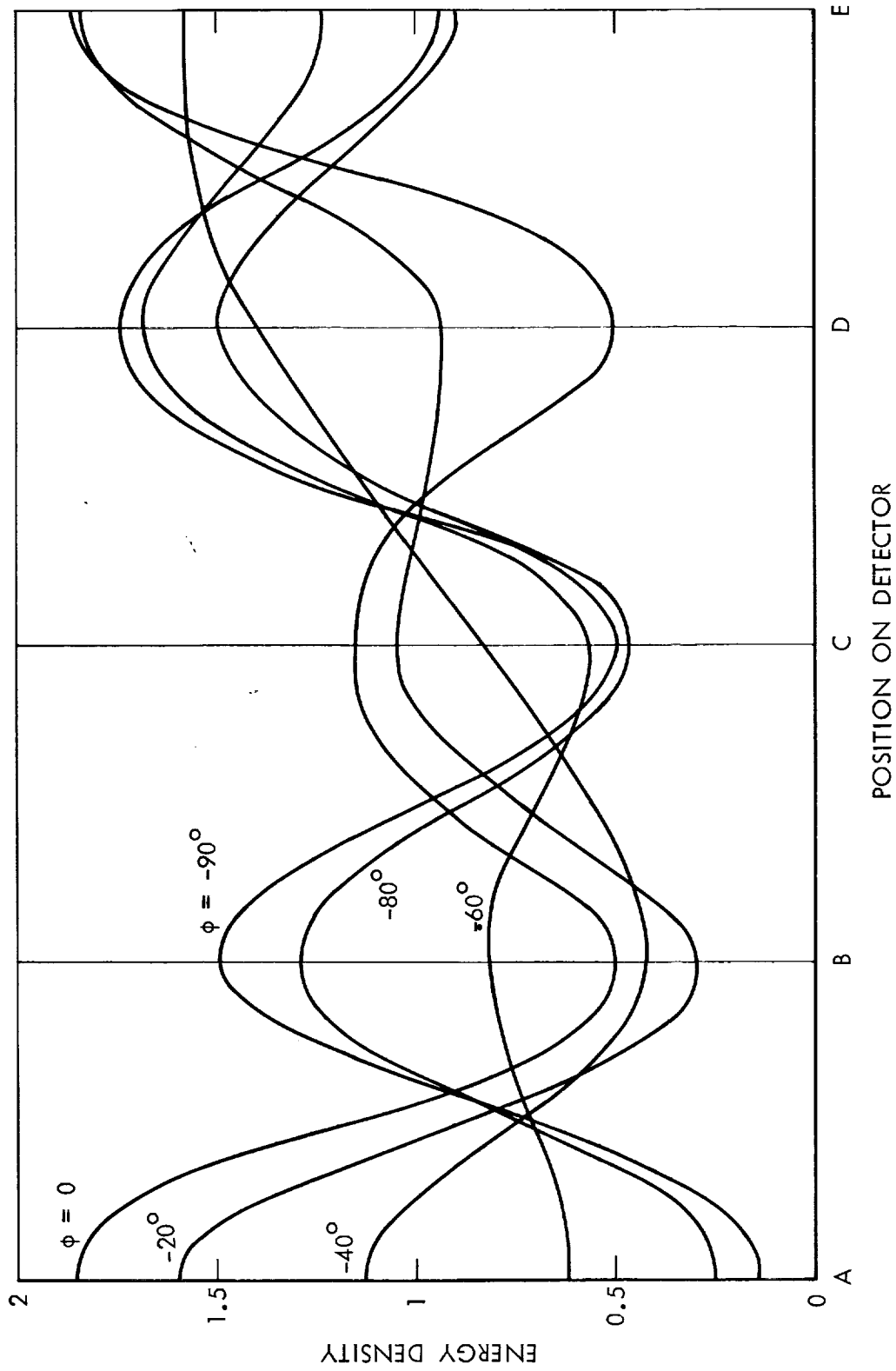


Figure 6-5. Energy Density Plots of Super Color Perception Detector for Values of Normalized Frequency d Between -90° and 0°

negative values of our normalized frequency ϕ between -180° and 0° . For positive values of ϕ , the curves should be rotated about the C position so that position A moves to the location of position E and vice-versa. The expressions for these energy distributions are derived in Appendix A.

The position marks A to E correspond to the sampling points in the demodulation process. To obtain $\sin \phi$ the function is sampled at points A and E. For $\sin 2\phi$ it is sampled at point B on the forward scan, and D on the reverse scan. For $\cos \phi$ the function is sampled at points A, C, and E. For $\cos 2\phi$ the function is sampled at all five points.

Figure 6-6 illustrates the waveforms that result in the demodulation processes for the case of $\phi = 0$. The set of curves for $\sin \phi$ and $\sin 2\phi$ shows the positive and negative phases separately and superimposed. The sets of curves for $\cos \phi$ and $\cos 2\phi$ show the waveform for positive and negative phase with two settings of the time scale, for the purpose of clarity. Thus, in the upper two curves for $\cos \phi$ and the lower two curves for $\cos 2\phi$, the time scale is expanded by a factor of two relative to the other curves.

Measurements were made for eight normalized wavelengths ϕ . These values of ϕ were -180° , -140° , -90° , -40° , 0° , 40° , 90° , 140° . Figures 6-7 and 6-8 give plots of the results of the demodulation process for these eight normalized wavelengths. The dashed curves show the ideal Fourier components and the solid lines connect the experimental data points. Since there were only eight data points, the experimental curves are not precisely defined, but one can at least see that the experimental results are reasonably good.

Since we do not know the sign of the experimental points close to zero, it has been necessary to represent each of these by a pair of points.

The Fourier components represent the ratios of the signals derived from the demodulation process to the average value of the modulated waveform which is obtained by filtering the input signal.

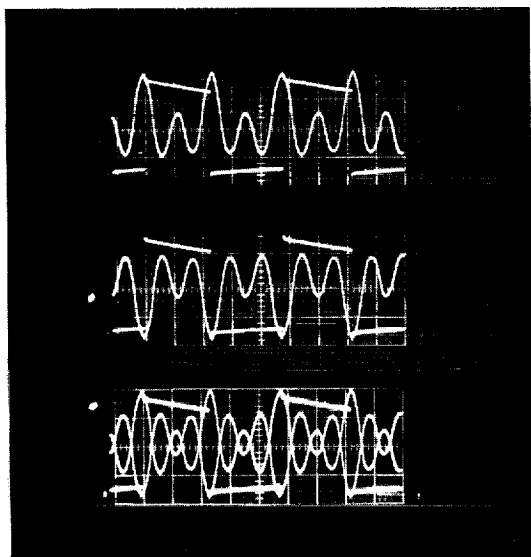
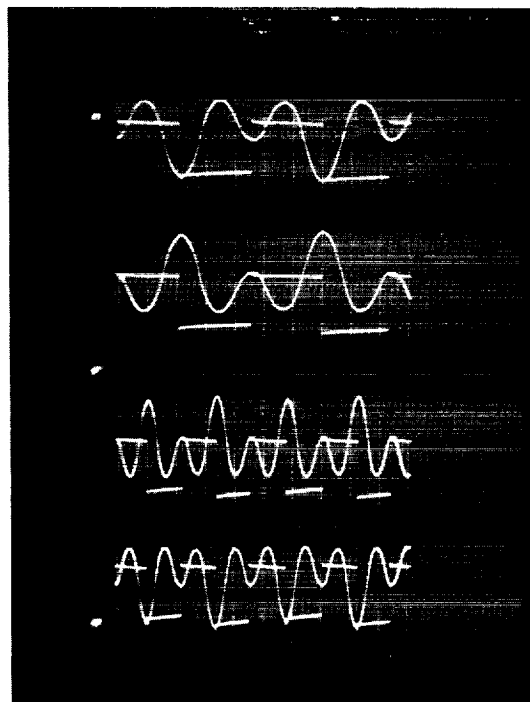
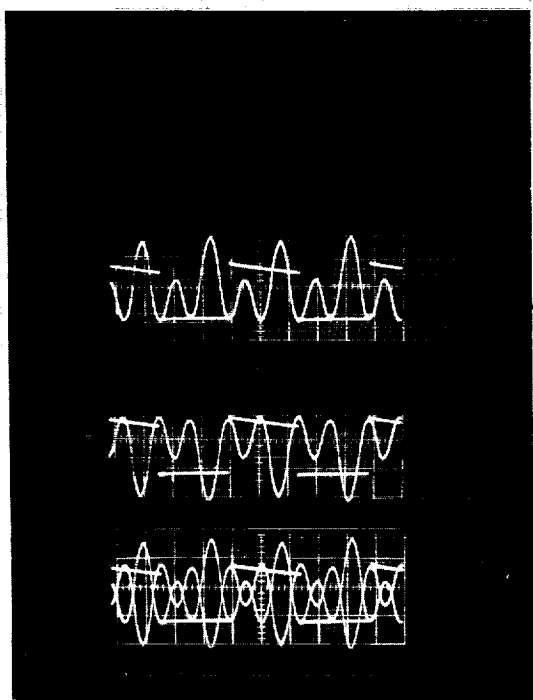
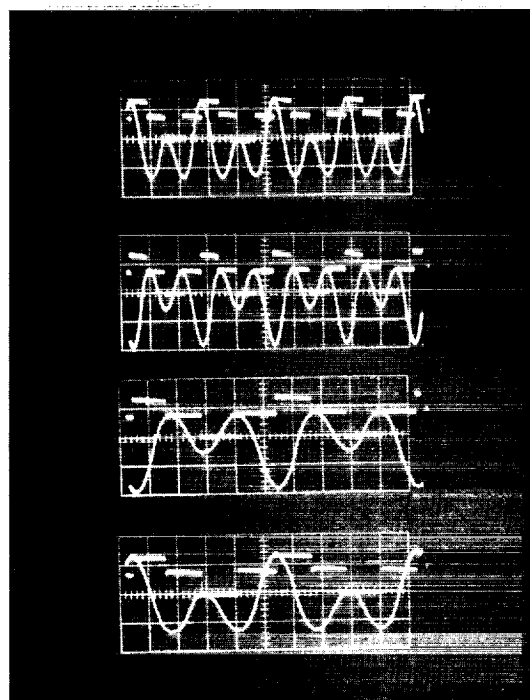
SIN ϕ COS ϕ SIN 2ϕ COS 2ϕ

Figure 6-6. Waveforms of Demodulated Processes in Super Color Perception Simulation for $d = 0$

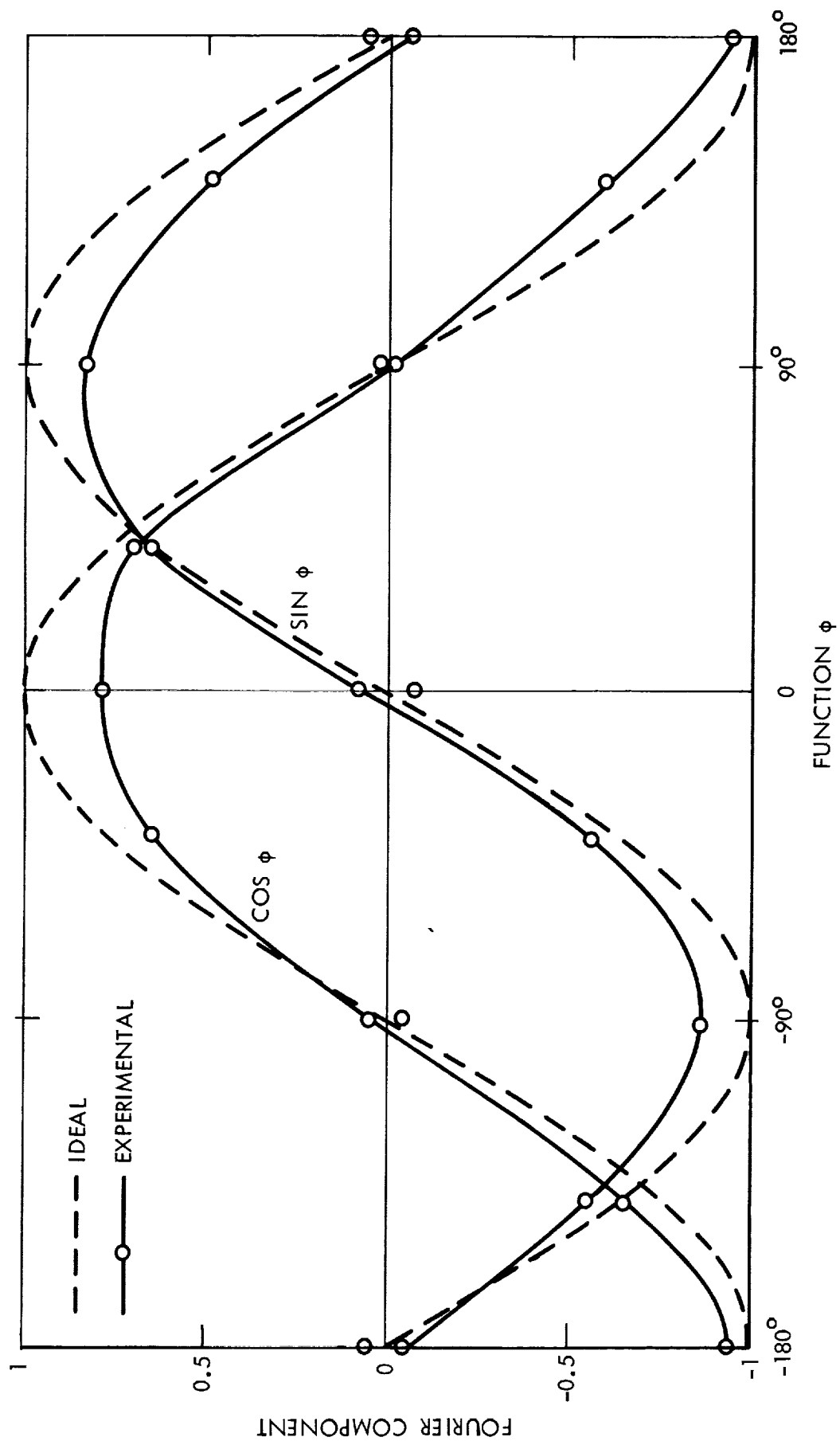


Figure 6-7. Value of First-Harmonic Fourier Component of Spectrum Measured in Simulation of Super Color Perception Compared with Ideal Values

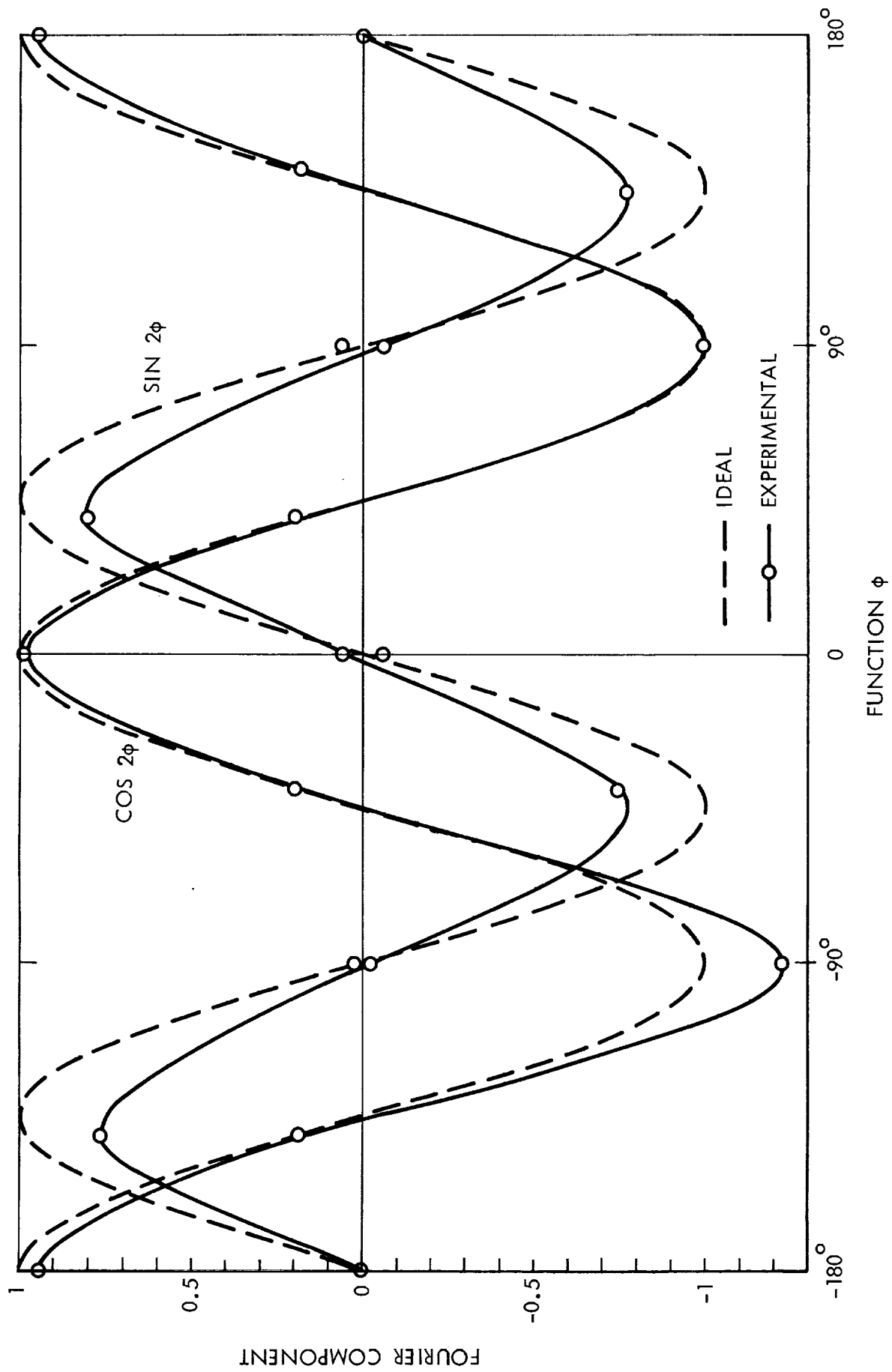


Figure 6-8. Value of Second-Harmonic Fourier Component of Spectrum Measured in Simulation of Super Color Perception Compared with Ideal Values

6.4 EXPERIMENTAL METHOD

The simulation process was performed as follows. An oscilloscope was modified to act as a function generator. A mask was placed on the face of the oscilloscope corresponding to the function to be generated. A photocell detected the beam emerging from the oscilloscope, and controlled the vertical deflection signal so that the beam followed the edge of the mask. The horizontal axis was activated by a triangular wave to produce the scanning process. The vertical deflection signal of the oscilloscope formed the modulated waveform.

The modulated waveform was filtered to obtain the d-c signal. It was then fed through a phase inverter and low-pass filter, and the two phases were fed through separate gates to a common clamper capacitor. The two gates were activated by pulse circuits that were synchronized to the triangular scanning waveform.

One of the difficulties with the function generator is that it was very inconvenient to set a zero reference level from which one could measure the d-c signal component. Therefore an artificial process had to be resorted to in the experiment. We measured the difference between the d-c level of the modulated waveform and the minimum value of the waveform, and we also measured the peak-to-peak value of the waveform. We then determined, from the original energy distribution plots, the ratio of the minimum value of the waveform (relative to the absolute zero level) divided by the peak-to-peak value. This ratio was multiplied by the measured peak-to-peak value and the resultant added to the measured d-c level (relative to the minimum value) to obtain the correct d-c level.

SECTION 7

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APPENDIX A

DERIVATION OF ENERGY DISTRIBUTIONS FOR
SUPER COLOR PERCEPTION

As was illustrated in Figures 6-4 and 6-5, the energy distribution on the detection element of our super color perception device are defined by five values labeled A, B, C, D, and E. These correspond to the values of the modulated waveforms at the sampling instants. By scanning the energy distributions, a modulated waveform is produced, and the values at the sampling instants follow the sequence:

$$(A, B, C, D, E, D, C, B) (A, B, C, \dots) \quad (A-1)$$

where the parenthesis set off the values in a given cycle. There are eight values in a given cycle, which shall be designated as X_1 to X_8 . Thus we have

$$A = X_1, B = X_2 = X_8, C = X_3 = X_7, D = X_4 = X_6, E = X_5 \quad (A-2)$$

Let us assume that there are four demodulation devices, which generate output signals given by

$$Z_1 = (1/2) (X_1 - X_5) \quad (A-3)$$

$$Z_2 = (1/4) (X_1 - X_3 + X_5 - X_7) \quad (A-4)$$

$$Z_3 = (1/2) (X_2 - X_6) \quad (A-5)$$

$$Z_4 = (1/8) (X_1 - X_2 + X_3 - X_4 + X_5 - X_6 + X_7 - X_8) \quad (A-6)$$

The average value of the waveform can be approximated by

$$Z_5 = (1/8) (X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 + X_8) \quad (A-7)$$

Let us define the functions f_1 to f_4 in accordance with

$$f_1 = Z_1/Z_5, f_2 = Z_2/Z_5, f_3 = Z_3/Z_5, f_4 = Z_4/Z_5 \quad (\text{A-8})$$

Combining Eqs. (A-2) to (A-8) gives

$$(8Z_5)f_1 = 4A - 4E \quad (\text{A-9})$$

$$(8Z_5)f_2 = 2A - 4C + 2E \quad (\text{A-10})$$

$$(8Z_5)f_3 = 4B - 4D \quad (\text{A-11})$$

$$(8Z_5)f_4 = A - 2B + 2C - 2D + E \quad (\text{A-12})$$

$$8Z_5 = A + 2B + 2C + 2D + E \quad (\text{A-13})$$

Substituting Eq. (A-13) into Eqs. (A-9) to (A-12) gives

$$0 = A(f_1 - 4) + B(2f_1) + C(2f_1) + D(2f_1) + E(f_1 + 4) \quad (\text{A-14})$$

$$0 = A(f_2 - 2) + B(2f_2) + C(2f_2 + 4) + D(2f_2) + E(f_2 - 2) \quad (\text{A-15})$$

$$0 = A(f_3) + B(2f_3 - 4) + C(2f_3) + D(2f_3 + f) + E(f_3) \quad (\text{A-16})$$

$$0 = A(f_4 - 1) + B(2f_4 + 2) + C(2f_4 - 2) + D(2f_4 + 2) + E(f_4 - 1) \quad (\text{A-17})$$

This gives us four equations with four unknowns. Therefore we can set any one of the unknowns arbitrarily. As a first step let us set A equal to unity. Solving Eqs. (A-14) to (A-17) then gives

$$A = 1 \quad (A-18)$$

$$B = (1 + f_3 - f_4) / (1 + f_1 + f_2 + f_4) \quad (A-19)$$

$$C = (1 - f_2 + f_4) / (1 + f_1 + f_2 + f_4) \quad (A-20)$$

$$D = (1 - f_3 - f_4) / (1 + f_1 + f_2 + f_4) \quad (A-21)$$

$$E = (1 - f_1 + f_2 + f_4) / (1 + f_1 + f_2 + f_4) \quad (A-22)$$

A simpler set of equations can be obtained if we set A equal to the denominator expression of the equations for B to E, as follows:

$$A = 1 + f_1 + f_2 + f_4 \quad (A-23)$$

For this value of A, the other values simplify to

$$B = 1 + f_3 - f_4 \quad (A-24)$$

$$C = 1 - f_2 + f_4 \quad (A-25)$$

$$D = 1 - f_3 - f_4 \quad (A-26)$$

$$E = 1 - f_1 + f_2 + f_4 \quad (A-27)$$

Let us relate the functions f_1 , f_2 , f_3 , and f_4 to the Fourier components of the spectrum, as follows

$$f_1 = K_1 \sin \phi \quad (A-28)$$

$$f_2 = K_2 \cos \phi \quad (A-29)$$

$$f_3 = K_3 \sin 2\phi \quad (A-30)$$

$$f_4 = K_4 \cos 2\phi \quad (A-31)$$

We must choose values of K such that A, B, C, D, and E are all positive. We would like the values of K to be roughly equal and to be as large as possible, so that all Fourier components can be accurately evaluated with nearly equivalent accuracy. Convenient values of K that satisfy these conditions are

$$K_1 = K_2 = 1/2. \quad K_3 = K_4 = 1/2 \sqrt{2} \quad (\text{A-32})$$

Substituting Eqs. (A-28) to (A-32) into Eqs. (A-23) to (A-27) gives

$$A = 1 + \frac{\sin \phi}{2 \sqrt{2}} + \frac{\cos \phi}{2 \sqrt{2}} + \frac{\cos 2\phi}{2} \quad (\text{A-33})$$

$$B = 1 + \frac{\sin 2\phi}{2} - \frac{\cos 2\phi}{2} \quad (\text{A-34})$$

$$C = 1 - \frac{\cos \phi}{2 \sqrt{2}} + \frac{\cos 2\phi}{2} \quad (\text{A-35})$$

$$D = 1 - \frac{\sin 2\phi}{2} - \frac{\cos 2\phi}{2} \quad (\text{A-36})$$

$$E = 1 - \frac{\sin \phi}{2 \sqrt{2}} + \frac{\cos \phi}{2 \sqrt{2}} + \frac{\cos 2\phi}{2} \quad (\text{A-37})$$

By Eqs. (A-8) and (A-32) the Fourier components are related to the demodulator outputs by

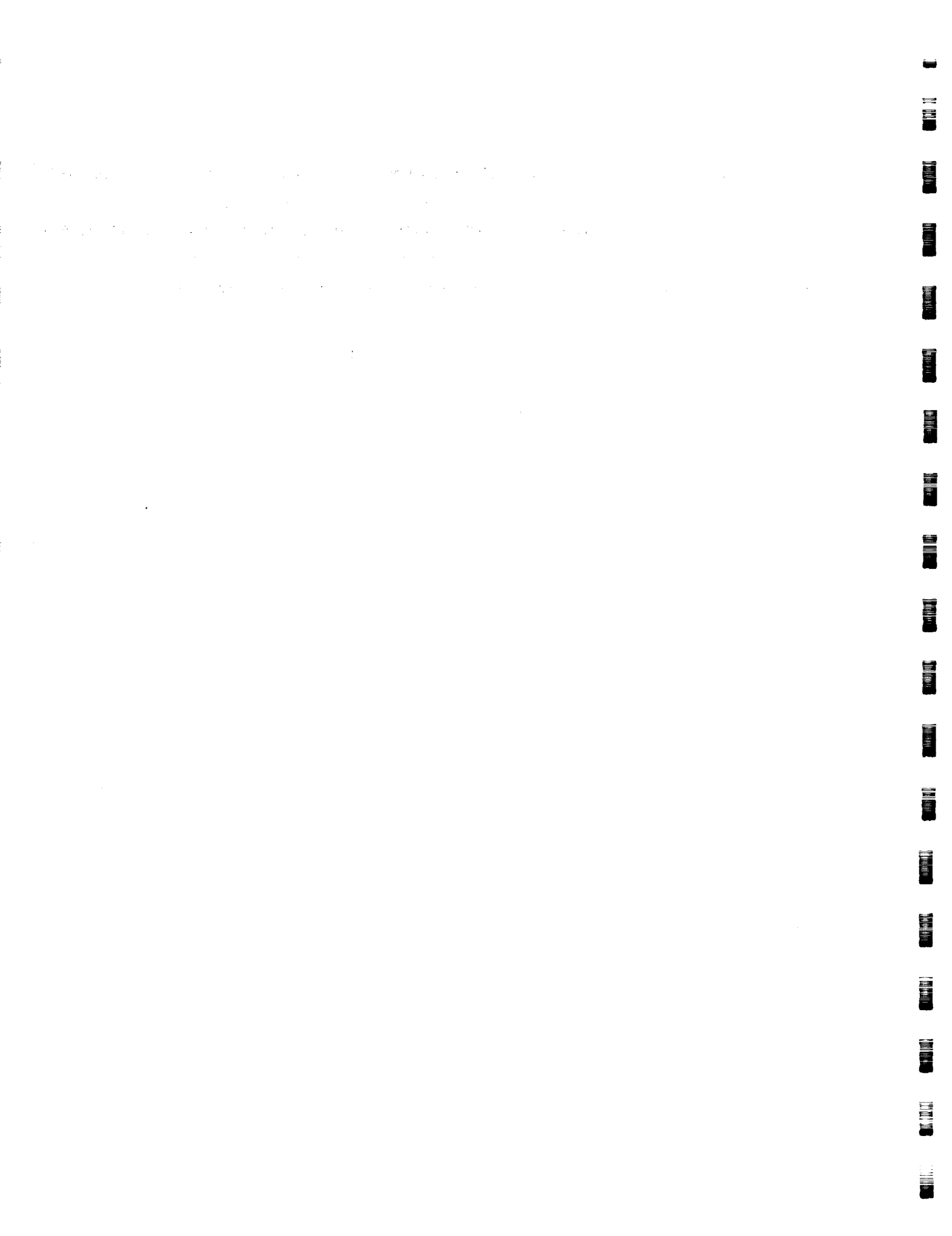
$$\sin \phi = f_1/K_1 = 2 \sqrt{2} \quad f_1 = 2 \sqrt{2} (Z_1/Z_5) \quad (\text{A-38})$$

$$\cos \phi = 2 \sqrt{2} \quad f_2 = 2 \sqrt{2} (Z_2/Z_5) \quad (\text{A-39})$$

$$\sin 2\phi = 2f_3 = 2(Z_3/Z_5) \quad (\text{A-40})$$

$$\cos 2\phi = 2f_4 = 2(Z_4/Z_5) \quad (\text{A-41})$$

The quantity Z_5 represents the average value of the modulated waveform, which is obtained by filtering that waveform. If we then feed the waveform into sampling demodulators of the type illustrated in Figure 8 of reference (12), the average values of the demodulator outputs have the values Z_1 , Z_2 , Z_3 , and Z_4 depending on the manner in which the sampling instants are synchronized with the modulated waveforms.



APPENDIX B

COMPARISON BETWEEN SPECTRAL SCANNING
THEORY AND CLASSICAL COLOR VISION THEORIES

(This material was originally issued as
Research Note #396, listed as reference (13).)

COMPARISON BETWEEN SPECTRAL
SCANNING THEORY AND CLASSICAL
COLOR VISION THEORIES

By

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16 May 1963

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1. INTRODUCTION

This memorandum compares the Spectral Scanning theory⁽¹⁾ with the classical theories of color vision. There is no one detailed theory of color vision that has general acceptance, but nevertheless there is nearly universal agreement in the basic principle of the receptor mechanism set forth by Thomas Young in 1801. A generalized statement of Young's postulate is that color vision is achieved by the signals generated in at least three different types of photosensitive elements with different spectral absorption responses. Essentially all theories of the receptor mechanism of color vision have been built on this principle. Most of these theories have assumed three different types of photosensitive elements, which was what Thomas Young believed, and are together referred to by the loosely defined term Trichromatic theory. Today the Trichromatic theory has very wide acceptance and so will be used as a standard of comparison for the Spectral Scanning theory.

The present status of the Trichromatic theory can be summarized as follows:

- (1) There is no direct physiological evidence to substantiate the Trichromatic Theory.
- (2) The primary indirect evidence represents (a) color-mixture psychophysical measurements, and (b) fairly recent spectrophotometer measurements of the retina, which was initiated by Rushton.
- (3) There are a great many contradictory psychophysical phenomena that the Trichromatic theory has not been able to explain satisfactorily.

Up to now there has been no alternative to the Thomas Young principle that has provided what has generally considered to be a plausible explanation of the receptor mechanism of color vision. This appears to be the main reason for the widespread belief in the Trichromatic theory, despite the theory's many limitations.

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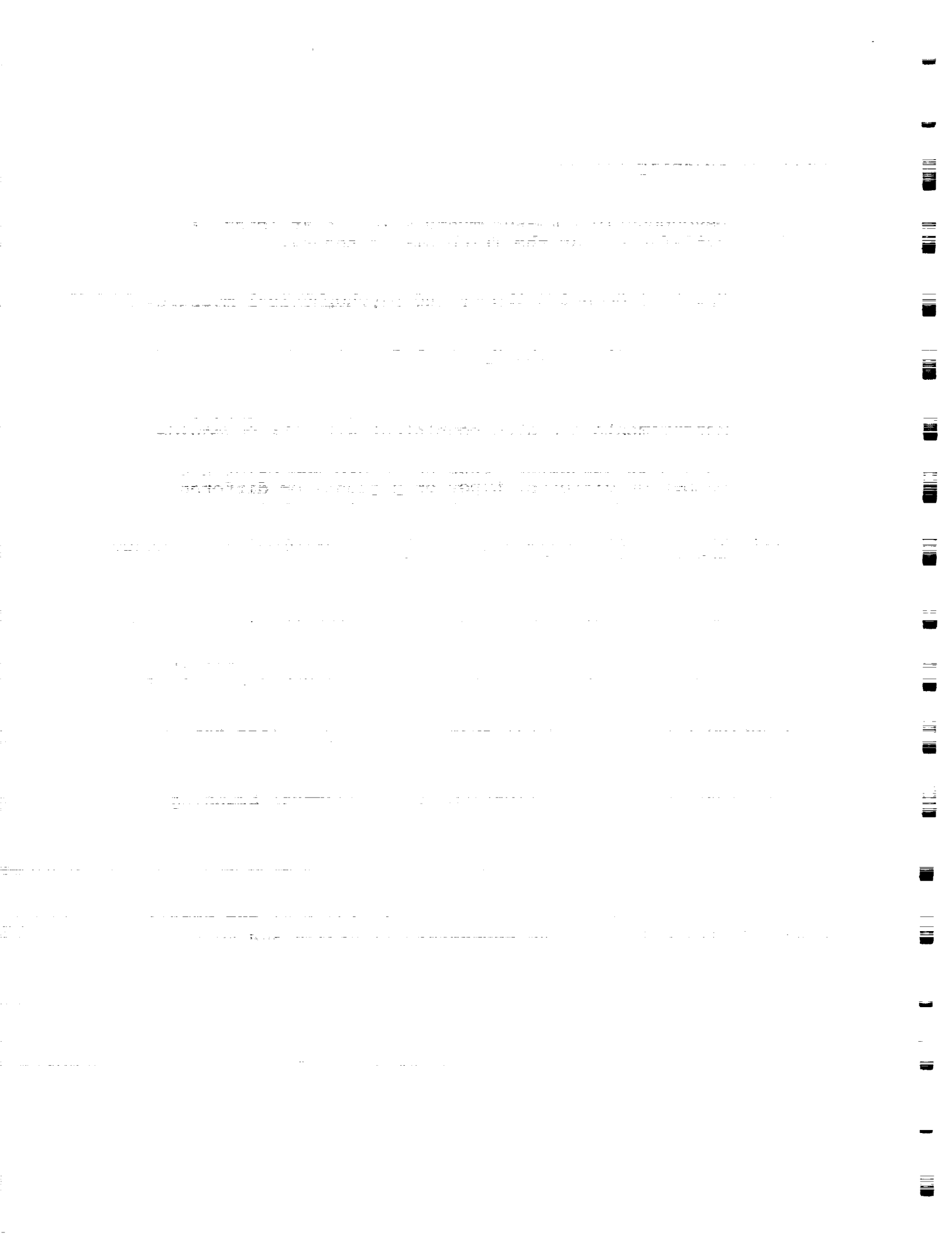
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In comparison, the following can be said relative to the Spectral Scanning theory:

- (1) The theory provides an explanation of color mixture psychophysical measurements which is at least as satisfactory as the Trichromatic theory.
- (2) There is a high degree of consistency between the Spectral Scanning theory and psychophysical measurements in general. The author has not found any important contradiction between a psychophysical measurement and the Spectral Scanning theory.
- (3) Re-evaluation of the spectrophotometer measurements of the retina by Rushton and others shows that these measurements are also consistent with the waveguide mode postulate of the Spectral Scanning theory. This data definitely does not prove the existence either of different types of pigments or different types of cones, as has been frequently assumed.
- (4) There already exists qualitative physiological evidence substantiating the Spectral Scanning theory in the waveguide mode effects known to exist in the outer segments of the cones, whereas there is no direct physiological evidence substantiating the Trichromatic theory. With further study of the waveguide mode patterns, it should soon be possible to provide quantitative agreement between color mixture experiments and the actual waveguide mode patterns in the receptors.

Considering that the Spectral Scanning theory is less than a year old, the evidence in its favor is remarkably great.

The most important implication of the Spectral Scanning theory is the explanation it gives of chromatic adaptation, which is described in Reference (6). The theory leads to the conclusion that chromatic adaptation is performed in terms of multi-dimensional spectral patterns represented by the spatial energy distributions in the photodetector region and by the modulated waveforms. This is in direct contrast with the classical concept that chromatic adaptation is performed in terms of three-dimensional trichromatic signals. By implementing chromatic adaptation in this manner, a visual system based on the Spectral Scanning theory could provide extremely accurate



spectral discrimination over great changes in level and chromaticity of the illuminant by means of natural feedback effects. In contrast, it appears very doubtful that anything approaching the spectral discrimination and adaptation capabilities of human vision could be built on the principle of the Trichromatic theory.

The Spectral Scanning theory opens up a great many new approaches for research in human vision, which include in particular the following:

- (1) A new approach to chromatic adaptation. The theory predicts that visual adaptation is multi-dimensional and so raises serious questions concerning the adequacy of our conventional three-dimensional color-matching experiments for studying visual adaptation.
- (2) A theoretical basis for definition of uniform color space. The proposed mechanism for the detection and adaptation processes of the receptors should provide the basis for a theoretical model of a uniform color space that could be very valuable in color standardization work.
- (3) Study of waveguide modes in receptors. The theory predicts the basic manner in which the shapes of waveguide modes in the outer segments of the cones are related to color mixture data. Thus a very clear direction for study of waveguide mode effects is indicated.
- (4) Study of flicker phenomena. The theory should provide a theoretical basis for explaining the complicated flicker fusion and Fechner color phenomena.

These represent just a few of the multitude of new areas of vision research in which the Spectral Scanning theory can provide a new direction of thinking.

This memorandum presents a detailed comparison of experimental evidence relative to the Spectral Scanning theory and the Trichromatic theory, and shows that the Spectral Scanning theory is at least as consistent with this evidence as the Trichromatic theory. A preliminary examination of the energy distributions produced by waveguide mode effects is made, and

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shows what appears to be the basis for agreement between waveguide mode patterns and color mixture data. As a supplement to this memorandum, Reference (6) gives a detailed discussion of visual adaptation relative to the Spectral Scanning theory.

2. RELATING WAVEGUIDE MODE PATTERNS TO COLOR MIXTURE DATA

The Spectra Scanning theory⁽¹⁾ postulated that the spatial distributions of energy across the cone for different wavelengths are produced by waveguide mode effects. However, no direct relation was shown between waveguide mode patterns and the spatial energy distributions predicted in the theory. The following discussion gives preliminary evidence for such a relationship.

The outer segments of the cones are shown by Enoch⁽²⁾ to act as cylindrical dielectric waveguides. Snitzer⁽³⁾ shows that the spatial energy distribution of a single mode in a cylindrical waveguide has circular symmetry about the axis of the cylinder, with a radial dependence proportional to the square of a Bessel function.

Figure 1 gives plots of the square of the first three Bessel functions. At low optical frequencies, only the mode corresponding to the zeroth-order Bessel function can propagate. As the frequency is increased (or the wavelength is decreased) the cut-off frequencies for higher modes are exceeded, and higher order modes that produce energy distributions defined by higher order Bessel functions can propagate. Thus we might expect that in the red wavelength region the J_0 distribution would predominate, in the green region the J_1 distribution would predominate, and in the blue region the J_3 distribution would predominate, as is indicated in Figure 1.

The exact parameters of the possible waveguide mode patterns are very difficult to calculate even when the waveguide characteristics are accurately established. The problem is further

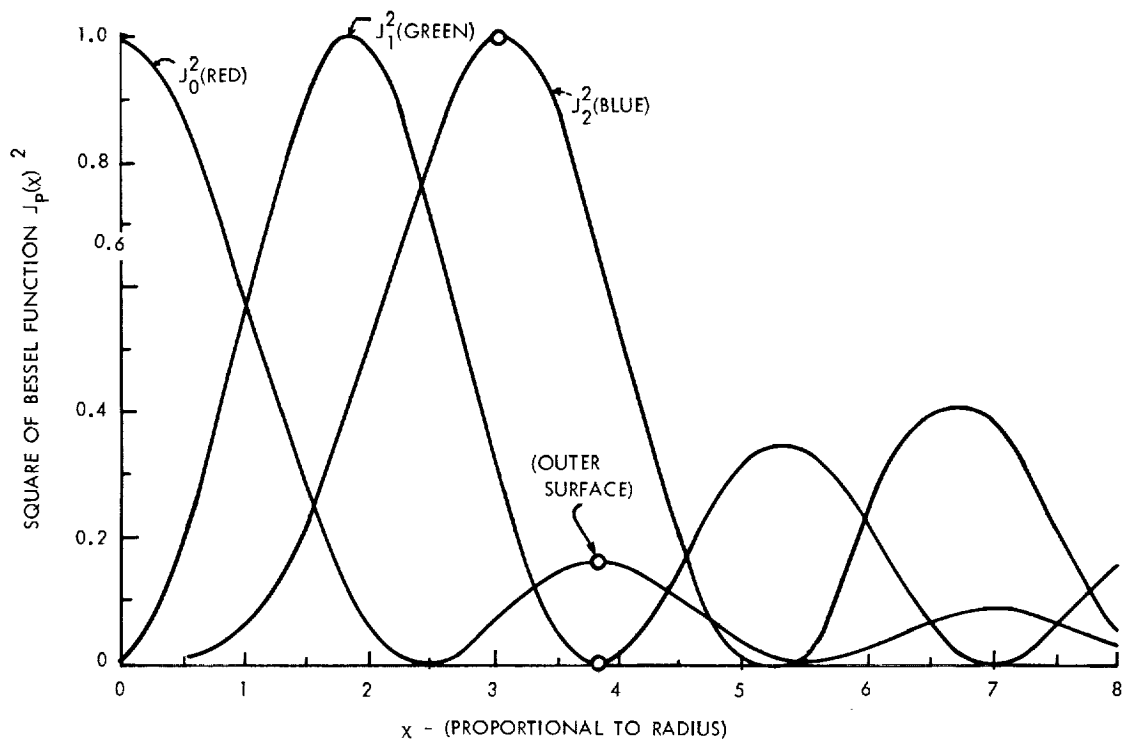


Figure 1. Squares of First Three Bessel Functions Showing Possible Relation to Wavelength Discrimination Effects

complicated by our lack of accurate knowledge of the dielectric characteristics of the receptors. Consequently, the following discussion will merely try to show qualitative relationships between waveguide mode patterns and the spatial energy distributions predicted in the Spectral Scanning theory. These qualitative relationships should be useful in pointing the way in which more intensive research on the waveguide mode effects in the receptors should progress.

Compare the Bessel function plots of Figure 1 with the calculated energy distributions across the cone for the Spectral Scanning theory given in Figure 10 of Reference (1). There is a great deal of similarity if we assume that Position 1.0 of the energy distribution plot (Figure 10 of Reference 1) represents the axis of the outer segment of the receptor and Position 0 represents the outer surface. Thus it appears that the variable "Position on Cone" approximately represents the relative radial distance measured from the outer surface. In the Bessel function plots of Figure 1, circles are drawn corresponding to the value of X at the outer surface of the receptor which give good agreement between the Bessel function plots and the predicted energy distributions of the theory. We are interested in the portions of the Bessel function plots for values of X up to the circled points.

The spatial energy distributions for deep blue (470m μ) and violet (445m μ) in Figure 10 of Reference (1) show anomalous humps in the region of Position 0.5. These probably are merely due to the assumptions made in the analysis. By assuming different demodulation approaches and changing certain assumptions, the anomalous humps can be eliminated.

There is enough similarity between the Bessel function plots and the calculated spectral energy distributions of the theory to indicate the possibility of a relationship between them. The spatial energy distributions for the theory can be varied somewhat

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3. The third part is a discussion of the results obtained.

4. The fourth part is a conclusion and a list of references.

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by assuming different demodulation process, and the Bessel function plots can be varied somewhat by assuming different detailed electromagnetic characteristics in the outer segment. Thus there is flexibility to account for discrepancies, but not so much flexibility that clear conclusions can not be drawn from the comparison.

From a knowledge of the gross dielectric characteristics of the outer segments of the cones we can determine the patterns of permissible waveguide modes. However, the actual mode patterns that do propagate may be determined by the ultra-microstructure of the outer segments. For example, a possible waveguide mode could be eliminated by means of infinitesimal discontinuities in the outer segment which provide high impedance paths for the circulating currents associated with that mode.

3. STANDARD OF COMPARISON FOR SPECTRAL SCANNING FOR THEORY

In 1801 Thomas Young proposed in essence that the neurological signals for color vision are derived from three different types of photosensitive elements* having different spectral absorption curves. This principle forms what is now generally called the Trichromatic theory.

Hundreds of theories of color vision have been built on this basic principle of Thomas Young. Most of them have assumed three types of photosensitive elements and so are Trichromatic theories. However some have assumed four or more types of photosensitive elements. Since this extension of the concept of Thomas Young to include more than three photosensitive elements does not represent a significant change of concept, we should consider all these theories as merely variations of the Thomas Young theory, even though they may not be Trichromatic theories.

* The author has avoided the use of the common term "receptor," and has instead used the more precise term "photosensitive element". A single cone is a receptor but could contain three different photosensitive elements.

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It is nearly universally believed today that the receptor mechanism must operate in accordance with the basic concept of Thomas Young. There is almost as great agreement that there are only three photosensitive elements, or in other words that the Trichromatic theory is correct.

The main reasons why there is such a strong belief that there can be only three photosensitive elements are as follows:

- (1) Since only three spectral responses are necessary, the use of more would represent useless redundancy.
- (2) If the color vision process has more than three independent channels of information, one cannot explain constancy of three-dimensional metameric matches. The assumption for explaining constancy of metameric matches is that two matching spectra evoke the same responses from each of the three spectral absorption curves, and so will always match regardless of the processing of the signals from the signals from the three absorption curves. If there are more than three independent spectral absorption curves, the signal processing for the separate channels must be inter-related in some complicated manner as yet unexplained.

The requirement of the Trichromatic theory for three different spectral absorption curves does not necessarily demand three different types of cones. The three absorption curves could be defined by three different photopigments arranged in different mixtures in four or more cones. The important requirement is that there be only three independent spectral absorption curves, which mathematically is equivalent to stating that the optical detection process must be three dimensional.

Thus we see that, if we accept the basic principle of Thomas Young, we appear to be forced to accept the same assumption he made, i.e., that there are only three different spectral absorption curves. We are forced to accept the Trichromatic theory, which demands that the optical detection process be three dimensional.

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In contrast, the Spectral Scanning theory proposes that a scanning process generates the spectral information, which is processed in a single channel. This theory leads to the conclusion that the detection process has a dimensionality much greater than three and that chromatic adaptation is performed in terms of this multi-dimensional information. Constancy of metameric matches is satisfied to the accuracy with which they really hold merely by requiring that the single channel be approximately linear.

From a practical point of view, if we are to compare the Spectral Scanning theory with other theories of color vision, we should limit the comparison to the Trichromatic theory because (1) the Trichromatic theory is nearly universally accepted, and (2) there are so many detailed theories of color vision it is virtually impossible to consider them all. Besides, the author has not been able to find any theory that proposes a plausible explanation of the receptor mechanism of color vision that is not based on the Thomas Young Principle. The essential difference between the Trichromatic theory and the Spectral Scanning theory is that the Trichromatic theory demands that the photopic optical detection mechanism be three dimensional whereas the Spectral Scanning theory demands that it generates a neurological signal of much higher dimensionality.

4. EXPERIMENTAL EVIDENCE

4.1 Basis for Confidence in Trichromatic Theory

The general acceptance of the Trichromatic theory in the field of color vision might lead one to think that it must be well substantiated by experimental data. However, this is not the case. The primary reason for its general acceptance seems to be that there has not been any good alternative.

Balaraman⁴ has presented a historical review of color vision and the Trichromatic theory in a recent issue of the Psychological

Bulletin (Harry Helson, Editor). His concluding statement is as follows:

"After more than a century of scientific research in color vision, the Trichromatic theory continues to face theoretical contradictions and unexplained facts. Trichromatic theorists everywhere should rigorously examine the theory's basic assumptions, provide much more experimental data on the basic visual functions, and honestly ask themselves the question, should the theory be subject to drastic revision or should it be replaced by some other theory?"

Let us compare the Trichromatic theory and Spectral Scanning theory in terms of how well they satisfy the experimental evidence.

4.2 Microscopic Evidence

Marriott⁵ has recently summarized the microscopic evidence for the Trichromatic theory as follows:

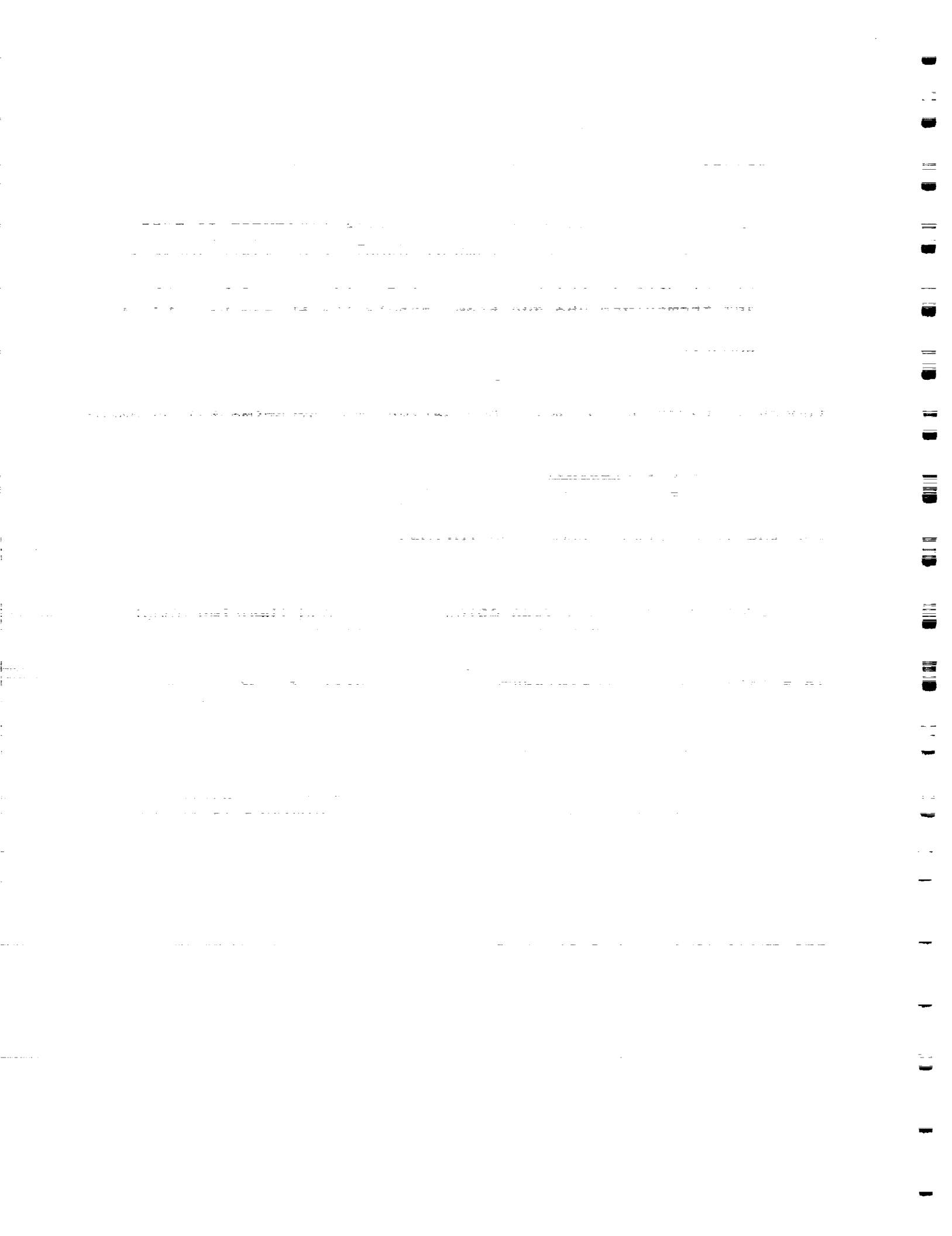
"So far, microscopic studies have revealed no differences in (the) structure or pigmentation (of the cones) that could be concerned with colour vision, and theories about different pigments and different types of receptor are based only on indirect evidence."

In a later section entitled "Experimental Basis for Theory," Marriott says:

"The Trichromatic theory is based primarily on the facts of colour matching and provides a simple and convincing explanation of the trivariance of normal color vision. Rushton's identification of the foveal pigments is strong confirmation of the theory."

Marriott goes on to discuss other psychophysical data, but more in the line of explaining contradictions rather than giving solid support for the Trichromatic theory. Thus it appears that that the above statement defines what Marriott feels is the major evidence for the Trichromatic theory.

Although there is no microscopic evidence for the Trichromatic theory there is microscopic evidence for the wave-guide mode effects postulated in the Spectral Scanning theory.



The dimensions and chemical characteristics are such that waveguide modes can be propagated. From a first approximation the theoretical mode patterns appear to be consistent with the energy distributions required in the theory. Enoch² has observed waveguide mode patterns that are qualitatively consistent with the Spectral Scanning theory.

On the other hand, an important problem in reconciling Enoch's microscopic observations with the Spectral Scanning theory is that the waveguide mode patterns Enoch observed for individual receptors show a great variability. This could be due to the effects of bleaching or damage to the retina in this measurements. In Enoch's measurements the retina is nearly completely bleached. A redeeming feature in this regard is that the adaptive effect of differential bleaching in the receptors under normal operation would tend to offset the effects of differences in waveguide patterns from cone to cone, just as it compensates for the effects of a changing illuminant spectrum.

4.3 Psychophysical Evidence

The primary evidence for the Trichromatic theory arose from the psychophysical data of color mixture. However this same data is also consistent with the Spectral Scanning theory and so cannot be used as a basis for comparing the two theories.

In the last few years Hurvich and Jameson have presented a great deal of psychophysical data to substantiate the opponent-process principle of the Hering theory. This is in direct agreement with the Spectral Scanning theory. However, one can also reconcile the Hering theory with the Trichromatic theory by postulating appropriate processing of the neurological information.

There have been many attempts to deduce the three primary spectral sensitivity curves of the Trichromatic theory from psychophysical experiments, but these efforts have been continually unsuccessful. Many different sets of curves have been derived by making different assumptions, but no one set has been proved to be unique.



As Balaraman has pointed out, there is a large amount of psychophysical evidence that presents serious questions to the Trichromatic theory. However one can build on the basic Trichromatic theory an infinite variety of postulates to explain detailed contradictions that arise from the data. Consequently it has as yet not been possible to conclusively disprove the basic Trichromatic theory by the psychophysical data.

The Spectral Scanning theory appears to satisfy the major psychophysical data at least qualitatively in a very natural manner. However this body of information is quite large and considerable research is required to achieve a detailed comparison of the theory with this data.

In the author's judgement the Spectral Scanning theory provides a considerably more parsimonious explanation of psychophysical data than does the Trichromatic theory. However the question of parsimony (regardless of how strong) involves value judgements that are difficult to defend against the hard forces of tradition.

This does not mean that it will be impossible to decide between the Spectral Scanning theory and the Trichromatic theory on the basis of psychophysical data. There is a very clear psychophysical point of difference between the theories. The Trichromatic theory contends that chromatic adaptation is definable by a three dimensional transformation, whereas the Spectral Scanning theory maintains that that transformation is performed in terms of data of a much higher dimensionality. Appropriate psychophysical research should be able to use this point of difference as a basis for designing crucial experiments to decide between the two theories.

4.4 Electrophysiological Measurements

Measurements of electrical signals within the retina have supplied very strong evidence to substantiate the Hering theory.

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The S-potentials originally measured by Svaetichin give responses as functions of wavelength which have the same shape as the spectral responses of the white-black, blue-yellow, and green-red opponent processes of the Hering theory.

A number of years ago Granit measured from the impulses in the optic nerve the responses of a number of spectral response curves, which led to the postulate of the polychromatic Dominator-Modulator theory by Granit. However the more recent discovery of the S-potentials by Svaetichin has indicated that Granit was probably measuring the peaks of the Hering-type opponent process signals and not the responses of spectral absorption curves.

Thus we can say that the electrophysiological experiments have given strong substantiation to the Hering theory but they cast little light on the validity of the Trichromatic theory.

A-C modulation signals have been measured in the retina, which is in agreement with the Spectral Scanning theory, but does not prove the theory's validity.

4.5 Chemistry of Visual Pigments

Work on the chemistry of the visual pigments has given very strong evidence to show that there is only one visual pigment in the cones, iodopsin, which has a spectral absorption curve that nearly matches the photopic luminosity curve of the eye. Discrepancies are easily explainable in terms of (1) macular pigmentation and (2) efficiency of transmission of different wavelengths down the outer segments of the cones.

This evidence is in direct agreement with the Spectral Scanning theory and offers serious difficulties to many versions of the Trichromatic theory. The usual belief by Trichromatic theorists is that the three spectral absorption curves are determined by the absorption curves of different photopigments. These theorists generally reject the strong evidence on the chemistry

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Figure 1. The effect of the number of trials on the number of correct responses. The number of correct responses was significantly higher than the number of incorrect responses in all conditions. Error bars represent the standard error of the mean.

of the visual pigments by maintaining that there is still a possibility that two other pigments exist in the cones, which have not yet been found.

4.6 Spectrophotometer Data

The only area where clear experimental evidence appears to exist to substantiate the Trichromatic theory is that of spectrophotometer measurements of the retina, work that was initiated by Rushton. Rushton compared the reflectivity spectrum of the retina before and after bleaching with various wavelengths and from this data was able to derive the spectral responses of what appeared to be a "green" and "red" pigment. He was unable to determine the response of a "blue" pigment, presumably because the reflectivity in the blue region was so low the effect of the "blue" pigment was lost in the noise of the experiment.

Rushton could not be sure from these experiments whether he was measuring the absorption spectra of different pigments or the response of one pigment and different filter effects. To answer this question he and Brindley shone lights of various wavelength through the sclera of the eye which reached the cones from a direction opposite to normal. Rushton found that the subject matched this light with roughly the same wavelength of a light in the normal direction. Rushton concluded from this experiment that filter effects could not be important in the color sensation and therefore his spectrophotometer measurements must be detecting different photopigments.

It is important to note, however, that Rushton's two pigments appear to act like a single pigment chemically, because he found that they regenerate at exactly the same rate. There is also a serious problem of reconciling this multiple pigment hypothesis with the failure of the chemical analysis to isolate the two pigments Rushton has appeared to find.

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Let us examine Rushton's results in terms of the Spectral Scanning theory. The theory proposes that waveguide mode effects in the outer segments of the cones produce different spatial distributions of energy for different wavelengths. Consequently bleaching with different wavelengths would produce different spatial patterns of bleached pigment across the cone. This would result in different spectral absorption curves as a function of the wavelength of bleaching, which is in agreement with Rushton's spectrophotometer measurements. The two spectral response peaks measured by Rushton could well be the effect of first and second order waveguide modes.

Rushton's experiment of shining the light through the sclera merely indicates that the waveguide mode effect to consider should be independent of the direction of transmission of light through the outer segment. We thus would conclude that the spatial variation of energy produced by the waveguide mode has a simple radial dependence, which is what one would have expected. The same basic waveguide mode patterns can be excited regardless of the direction of the light through the outer segment of the cone.

Thus we see that at least in a qualitative sense Rushton's experiments do not conflict with the Spectral Scanning theory. Further work on the waveguide mode effects is needed to prove quantitative agreement.

Micro-spectrophotometer measurements of the outer segments of individual cones in crushed fish retina have been made by William Marks at Johns Hopkins University, which have appeared to indicate the presence of three different types of cones with peak spectral responses in the red, green, and blue regions. However one can interpret this result in terms of the Spectral Scanning theory by assuming that for some reason different waveguide modes are accentuated in different cones. This may be due to such effects as the difference in angle with which the light hits the outer segment, the state of preadaptation of the cones,

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the chemical characteristics of the region that surrounds the cone, mechanical effects on the cones of crushing the retina, etc.

These micro-spectrophotometer measurements of the cones are of course extremely significant. However there is good reason to believe that with proper research they can be reconciled with the waveguide-mode postulate of the Spectral Scanning theory.

5. Conclusions Concerning Experimental Evidence

When we evaluate the experimental evidence objectively we must accept the conclusion that the Spectral Scanning theory is in at least as good agreement with the evidence as the Trichromatic theory. There do not appear to be any areas where serious contradiction exist that could necessitate large changes in the premises of the Spectral Scanning theory. However there is great need for research into many areas to provide detailed evaluation of the theory in terms of the experimental data.

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6. G. Biernson, Research Note No. 395, Applied Research Laboratory May 1963.

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APPENDIX C

AN EXPLANATION OF VISUAL ADAPTATION
IN ACCORDANCE WITH THE
SPECTRAL SCANNING THEORY

(This material was originally issued as Research
Note #395, listed as reference (14).)

AN EXPLANATION OF VISUAL ADAPTATION IN ACCORDANCE
WITH THE SPECTRAL SCANNING THEORY

By
George Biernson

May 1963

APPLIED RESEARCH LABORATORY
SYLVANIA ELECTRONIC SYSTEMS
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SECTION 1

IMPLICATIONS OF SPECTRAL SCANNING IN VISUAL ADAPTATION

This memorandum extends the Spectral Scanning theory¹ of color vision to include visual adaptation. It shows that the theory provides a new approach to this phenomenon, which has many important implications in the science of color vision. If we accept the Spectral Scanning theory, we are led to the conclusion that the main aspects of chromatic and achromatic adaptation would be performed prior to the demodulation process that generates the trichromatic signals. In other words, visual adaptation would be performed in terms of the spectral pattern information, as represented by the spatial energy distributions, and the modulated waveforms produced by scanning the spatial energy distributions. Since the spectral pattern information is more than three dimensional, the Spectral Scanning theory represents a multi-dimensional theory of color vision. This is in direct contrast to the classical three-dimensional concept of color vision embodied in the Trichromatic theory.

Let us clarify what we mean by dimensionality. A spectrum of light may be considered as having infinite dimensions, because an infinite number of values are theoretically required to define the spectrum exactly. For example, one can describe a spectrum by specifying its values at every wavelength, and a great number of wavelengths are required for accurate specification of certain spectra. Each wavelength can be considered mathematically as representing a dimension in multi-dimensional space, and the value of the spectrum at a given wavelength is the coordinate for that dimension.

According to the most common version of the Trichromatic theory, the retina has three types of cones, each having a different photopigment. Each cone is sensitive only to the relative power of the spectrum of the incident light weighted by

the absorption spectrum of the pigment in the cone. A single cone therefore generates a one-dimensional visual signal, and the combination of the signals from the three cones forms a three dimensional color signal.

In contrast, the Spectral Scanning theory postulates that the infinite dimensional light spectrum is converted by the waveguide mode effect to form a spectral pattern, which is then processed in the performance of visual adaptation. The processed spectral-pattern information is finally demodulated to generate the three-dimensional color signals. Because of the limited wavelength resolution of the waveguide mode effect, the spectral pattern is not infinite dimensional, but it undoubtedly has a dimensionality much higher than three.

The implementation of visual adaptation in terms of multi-dimensional spectral patterns can allow considerably greater accuracy of spectral discriminations than would be achievable if adaptation were performed in terms of three dimensional color signals carried in separate channels. Natural chemical feedback processes associated with photopigment bleaching can translate the light from an object into a spectral pattern that accurately describes the ratio of the spectrum of the object to the time average spectrum that the cone has received. Assuming that this time average spectrum represents the spectrum of the illuminant, the chemical feedback thereby compensates for the spectrum of the illuminant and generates a spectral pattern corresponding directly to the reflectivity spectrum of the object.

Multi-dimensionality in the spectral pattern would assure that very small variations in spectra would produce detectable differences in spectral patterns for wide ranges of illuminant spectra and object reflectance spectra. This would allow the eye to detect with high accuracy very small amounts of chromaticity in the reflectivity spectrum of an object, and very small differences in the reflectivity spectra of two neighboring objects.

[illegible]

Thus the Spectral Scanning theory provides a basis for a new theoretical approach to the visual adaptation process. This approach appears to have the potentiality of explaining quantitatively how the eye is able to achieve such great fidelity of interpreting the reflectivity spectra of objects in an invariant manner, as the illuminant is varied over great ranges of intensity and chromaticity.

SECTION 2

ACHROMATIC VISUAL ADAPTATION PROCESS

Chromatic adaptation can be best understood by considering first the achromatic adaptation processes. Various feedback processes are required to adjust the characteristics of the receptors so that they are kept in accurate calibration while the visual system adjusts to different light intensities.

One of the key factors in visual adaptation is the continual motion of the eye over the field of view. This consists of small involuntary motions that the eye cannot control plus the larger motions of the eye that are under voluntary control. This motion allows the separate receptors to become individually adapted to the average background illumination, and is an important factor in keeping the visual system in calibration.

This motion of the eye can be eliminated by artificially stabilizing an image on the retina, moving the image to compensate for eye motions.^{2,3} When this is done the image fades out in less than a minute, chromatic and achromatic sensations fading out simultaneously.

The primary mechanism associated with the slowly varying aspects of visual adaptation is the bleaching of the photopigments in the receptors. When a photon of light is absorbed by a photopigment molecule, the molecule is immediately isomerized (i.e., its physical configuration is changed). This initiates a chemical process that results in the bleaching of the molecule.⁴

There is a regeneration process that converts the bleached molecules back to photopigment molecules. The rate of regeneration is proportional to the concentration of bleached molecules. If the incident light is removed (so that there is no bleaching) the concentration of bleached molecules is reduced to 37 percent in a time measured by Rushton^{5,6,7,17} to be about 2 minutes for cones and 10 minutes for rods. This time will be called the regeneration time constant τ_r .

the eye adapts to a given illumination as follows. The incident light bleaches the pigment molecules, causing the concentration of bleached molecules to increase. The greater the concentration of bleached molecules, the faster the molecules are regenerated. Therefore an equilibrium state is eventually reached at which the bleached molecules reaches the concentration for which the regeneration rate is equal to the rate of bleaching by the light.

When a pigment molecule is bleached, it appears likely that the chemical process produces some form of charge differential which generates a flow of current. Since regeneration is the reverse process electrically to bleaching, it is a reasonable hypothesis that the regeneration of a molecule of photopigment produces a current that is equal and opposite to that produced by bleaching a molecule of photopigment. Thus the photopigment region would act as a balanced detector which delivers as an output the difference between the currents produced by bleaching and regeneration. Under equilibrium conditions the bleaching and regeneration currents are equal, and no net current is delivered. Raising the light intensity produces an excess of bleaching current, and an output current of one polarity is produced. Lowering the light produces an output current of opposite polarity.

This concept of a balanced detector is consistent with Hering's postulate that the eye has a black-white opponent-process substance. For a grey object the receptor delivers no signal, because this represents the equilibrium condition. A white object delivers more light than the average and so produces a signal of one polarity, whereas a black object delivers less light than the average and so produces an opposing signal.

From a psychological point of view it is very desirable that the black sensation is produced by a signal generated directly in the optical detection process, because black is

just as real a color sensation as are the other basic colors: white, blue, yellow, green, and red. However, Dr. F. Dimmick pointed out to the author that there is also a seventh color sensation, grey, that should be included in the color theory.

The sensation of grey could result from the way the color data is transmitted along the optic nerve to the brain. It appears likely that the neural signals of an opponent pair of colors are sent in a balanced fashion down two optic nerve fibers. One fiber fires when the stimulating light is turned on, and so transmits the white signal, while the opposing fiber fires when the light is turned off, and so gives the black signal. There is a low quiescent firing level in all nerve fibers which would tend to obscure the signal. However, if the brain subtracted the outputs from the two opposing nerve fibers the quiescent firing rates would tend to cancel out, and a high resolution black-white opponent signal would be produced. The brain may also be sensitive to the sum of the two signals from the two nerve fibers and this sum signal could give rise to the grey sensation.

Thus the concept of a grey sensation is consistent with the Spectral Scanning theory, but would be produced by neurological processes that follow the receptor. The receptor itself would initiate only the six opposing color sensations, white, black, blue, yellow, green, and red.

The opposing current due to regeneration that has been hypothesized would produce shot noise because of the discrete nature of the electron flow. The author calculated this shot noise and determined from it the visual threshold that it would produce for various concentration of visual pigment.⁸ He found that this agreed with measured data taken by Baker⁹ within a factor of two, which is within the accuracy of certain assumptions required in the author's calculation. This data represented the visual thresholds of the rods measured 2 seconds after the start of dark adaptation: after the neurological transients had ended, but before there was significant change in the concentration of bleached pigment.

ness there is good evidence to substantiate the balanced detector hypothesis. Without this hypothesis there does not appear to be any good explanation of the relationship between visual threshold and photopigment concentration. This is an important point, because as will be shown the balanced-detector assumption is a very important element in the explanation of the visual adaptation process.

An important factor to consider in explaining visual adaptation is the tremendous dynamic range of the retina. The eye has a dynamic range of about 100 decibels, i.e., the maximum light intensity that can be safely tolerated is 10^{10} times larger than the minimum detectable light intensity. The iris varies the light intensity by a factor of 16. Bleaching of molecules reduces the effective light intensity, because the quantum efficiency is proportional to the concentration of photopigment. However, this reduction in quantum efficiency is significant only at high intensities, and has a maximum reduction of about 8. Thus the iris and bleaching change the effective light intensity by a factor of 128, or somewhat more than 20 decibels. Since the total dynamic range of the eye is about 100 decibels, the ratio of maximum to minimum incident power that is effectively absorbed is 10^8 (or 80 decibels).

Each photon that is effective bleaches one molecule of photopigment. Hence the maximum rate of molecular bleaching in a receptor is 10^8 times greater than the minimum rate of bleaching. Since bleaching in some way generates an electrical current, one can consider that the receptor has an input current that varies over the fantastic range of 10^8 to one.

The optic nerve has a very low dynamic range, because it sends messages to the brain coded in terms of a pulse rate. Since the number of quanta of information that can be supplied depends on the time interval chosen, it is difficult to define the dynamic range of the optic nerve. However, one can conservatively estimate that the dynamic range of a nerve fiber is no greater than 100 to one. Since the input current to the

retina varies by a factor of 10^5 , there must be a compensatory gain change of one million to one (i.e., 10^6) in the retina.

Part of the million-to-one gain change is probably achieved by the manner in which the signals from the receptors are integrated together in the bipolar cells. However, there can be little doubt that a very large part of this gain variation must be achieved within the receptors themselves. The requirement that the receptors achieve accuracy of calibration over this very large variation of gain is an important constraint in the possible operation of the visual adaption process.

In this discussion we have ignored for the purpose of simplicity the differences between rods and cones with respect to this adjustment of gain. While these effects are important they do not alter the general conclusions.

How are the separate receptors kept in calibration with one another as the gains are adjusted over such a large range? It seems essential that each receptor have some form of feedback control of gain. The feedback loop should have a very long time constant so that the variations from receptors to receptor are not erased by the feedback loop. It appears logical that this feedback loop should have a time constant roughly equivalent to the time constant of photopigment regeneration, which is 2 minutes for cones and 10 minutes for rods. This idea that the receptors have a slow feedback loop to control their individual gains has been previously proposed by Boynton.¹⁰

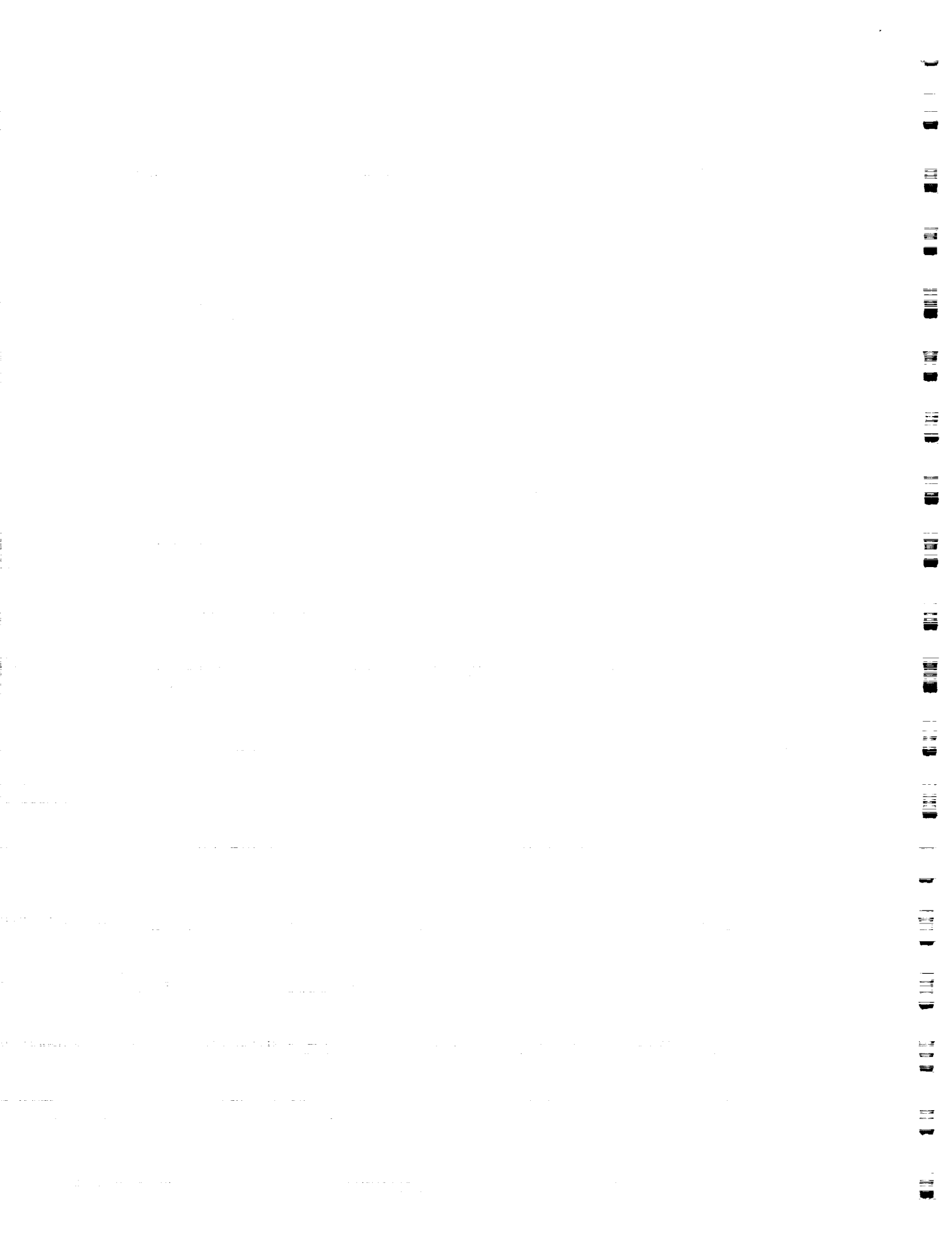
There is good reason to believe that there are other factors that assist in the control of the gains of the individual receptors. It is very difficult for a single feedback loop to achieve the very large change of gain that is required, and so it is likely that the receptors use an additional gain adjustment technique to make the task simpler for the feedback loop.

The most important factor in a gain-control operation is the information used to control the gain. The receptor might control its gain as a function of the concentration of bleached pigment, the higher the concentration the lower the gain. However, it is difficult to see how the bleached pigment concentration itself could be conveniently measured to control the gain. An alternative hypothesis is that the receptor is able to detect the regeneration current independently of the bleaching current and uses the value of the regeneration current to control the gain. Since the regeneration current is proportional to the concentration of bleached pigment, its value would have the same effect in the control.

Another possibility is that the receptor is able to sense the sum of the bleaching and regeneration currents, and uses this sum to control the amplifier. As will be shown there is strong reason to believe that this is what is done. However, it is simpler to describe the adaptation process if the regeneration current alone is used for gain control, and so this will be assumed in the detailed discussion of the system.

Figure 1 gives a block diagram showing a possible means by which the gain and bias of an individual receptor could be controlled. This diagram may not be completely accurate, but it probably gives at least a reasonable first approximation of the actual system.

The incident light P_i (expressed in photons per second per receptor) is multiplied by the quantum efficiency $\eta(\lambda)$ to give the effective photon rate per receptor. The efficiency η varies with wavelength λ in proportion to the scopic luminosity curve for the rods and in proportion to the photopic luminosity curve for the cones. The maximum efficiency is about 0.1 for rods and is probably about the same for the cones. The difference in sensitivity of the cones and rods at low light intensities appears to be caused by (1) the inherent noise level in the cones being about 14 times that of the rods and (2) the integration area of the rods being about 50 times that of the cones.⁷



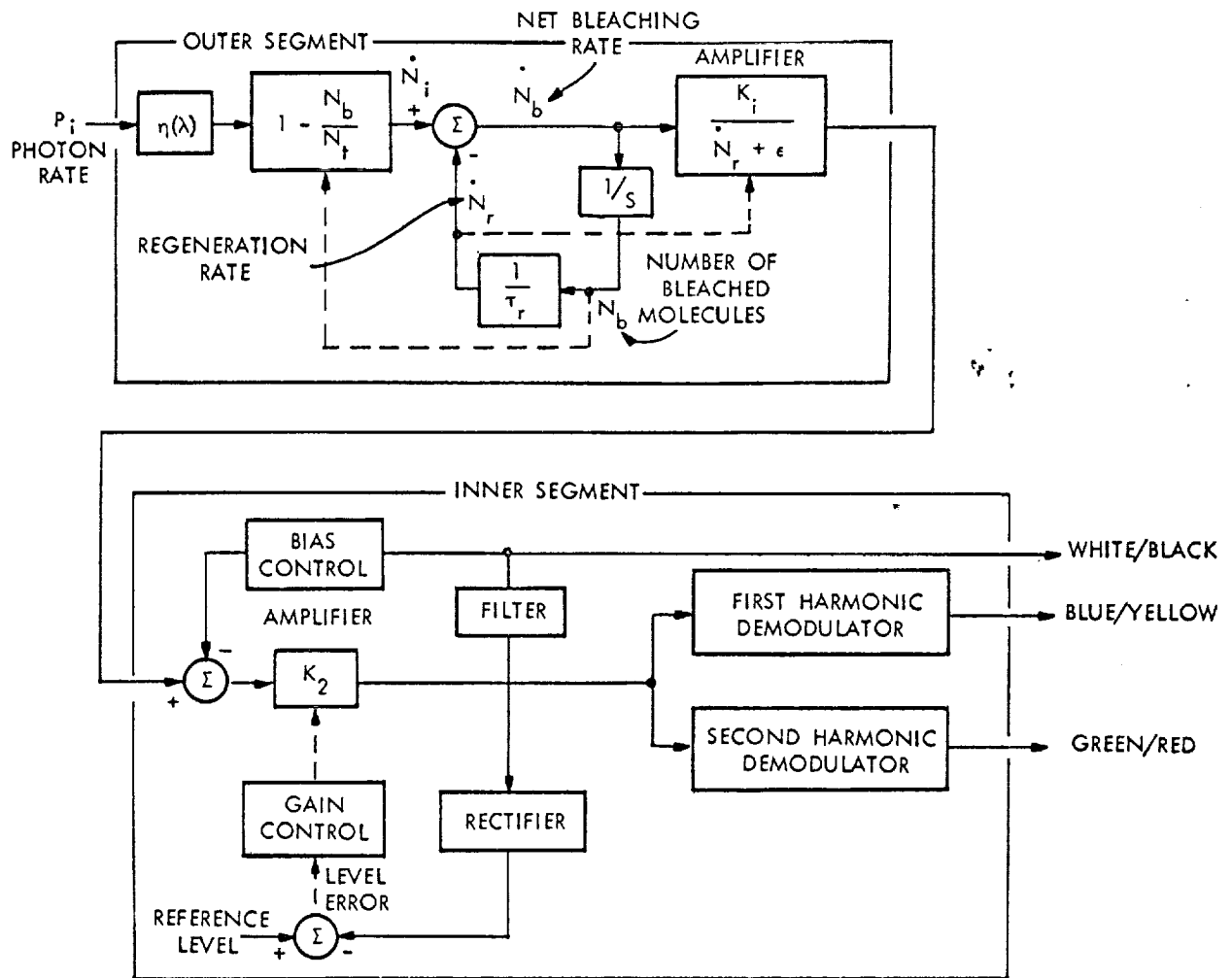
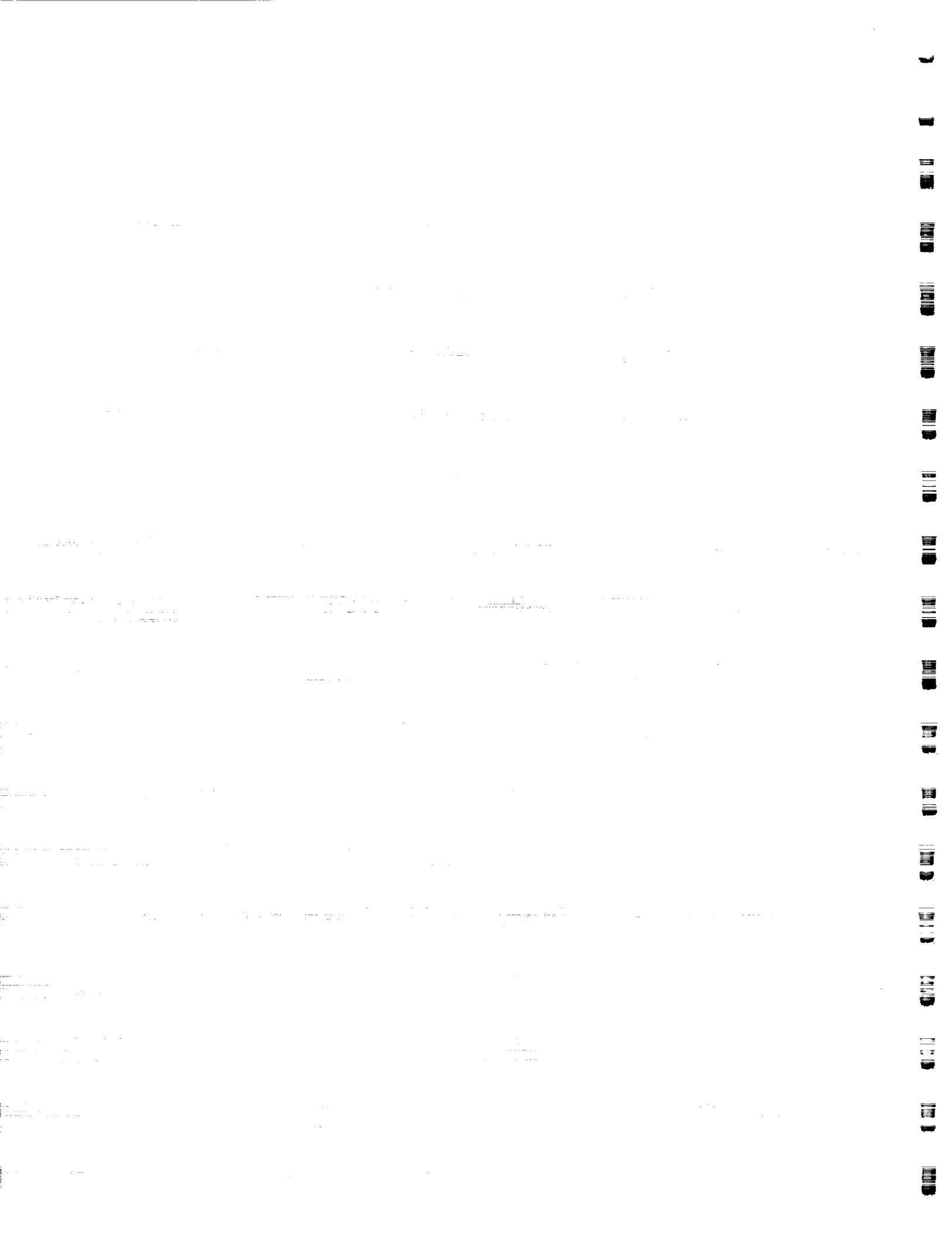


Figure 1. Possible System For Controlling Gain and Bias of Individual Receptor



The effective quantum efficiency varies in proportion to the concentration of photopigment. This effect is indicated by the factor $(1 - N_b/N_t)$, where N_b is the number of bleached pigment molecules and N_t is the total number of pigment molecules, unbleached plus bleached. Under normal lighting conditions the concentration of bleached pigment is quite small. It is only at very high intensities that this factor $(1 - N_b/N_t)$ departs significantly from unity, and it has a minimum value of about 1/8 at maximum light intensity.

The rate of bleaching of photopigment molecules by the light is indicated as \dot{N}_l and the rate of regeneration of the photopigment molecules is indicated as \dot{N}_r . The difference between these two rates is the net rate of change of bleached molecules \dot{N}_b , which defines the net signal developed in the balanced detection process. The number of bleached molecules N_b is the time integral of the net bleaching rate \dot{N}_b . This integration action is represented in the block diagram by the LaPlace transform operator $(1/s)$ by the expression

$$N_b = (1/s) \dot{N}_b \quad (1)$$

In a non-rigorous sense the LaPlace operator (s) may be considered to be equivalent to the differential operator (d/dt) . The regeneration rate is related to the concentration of bleached pigment by

$$\dot{N}_r = N_b/\tau_r \quad (2)$$

where τ_r is the regeneration time constant. Rushton has measured τ_r to be about 10 minutes for rods and 2 minutes for cones.

It seems essential that there be some amplification process in the outer segment because of the tremendous dynamic range and sensitivity of the receptor. If the receptor is to use information concerning the concentration of bleached pigment, or

the regeneration current, to control its gain (which appears to be necessary for effective control), it is logical that it would be the gain in the outer segment that is controlled by this information. Thus the block diagram shows a variable gain element in the outer segment represented by the transfer function $K_1/(\dot{N}_r + \epsilon)$. This would approximately vary the gain inversely with the regeneration rate \dot{N}_r , producing high gain at maximum dark adaptation when the regeneration rate is low and low gain under light adaptation conditions. The small factor ϵ is added to \dot{N}_r in order to keep the gain from becoming infinite when \dot{N}_r is zero.

Another possibility is that the receptor uses for gain control the sum of the magnitudes of the regeneration and bleaching currents, which is proportional to $(\dot{N}_r + \dot{N}_b)$. The amplification transfer function would then be $K_1/(\dot{N}_r + \dot{N}_b)$. The signal E delivered by the outer segment would be

$$E = K_1 \left[\frac{\dot{N}_b - \dot{N}_r}{\dot{N}_b + \dot{N}_r} \right] \quad (3)$$

For convenience let us consider a normalized signal X equal to E/K_1 . Now the bleaching rate \dot{N}_b is proportional to the instantaneous input light power P_1 , and the regeneration rate \dot{N}_r is proportional to the average value P_0 of the input light power. Hence the normalized signal X delivered by the outer segment can be represented as

$$X = \left[\frac{P_1 - P_0}{P_1 + P_0} \right] \quad (4)$$

This control relation has the important advantage that the normalized signal X never exceeds the limits of ± 1 . It has a value of zero for a neutral grey object, a value of -1 for a completely black object, and never exceeds $+1$ for the brightest white object. Thus the control keeps the signal within a fixed operating range of the receiver.



Vilma¹¹ theorized that in order for an individual to perceive object colors essentially independently of changes of the spectrum of the illuminant the chromatic adaptation process must approximately follow a transformation law of the form of the Lorentz transformation of Special Relativity. The same line of reasoning would lead one to predict that the achromatic adaptation process to different light intensities should also follow a Lorentz Transformation. It can be shown that the control law represented in Eq. (4) corresponds to a Lorentz transformation in perceptual coordinates.

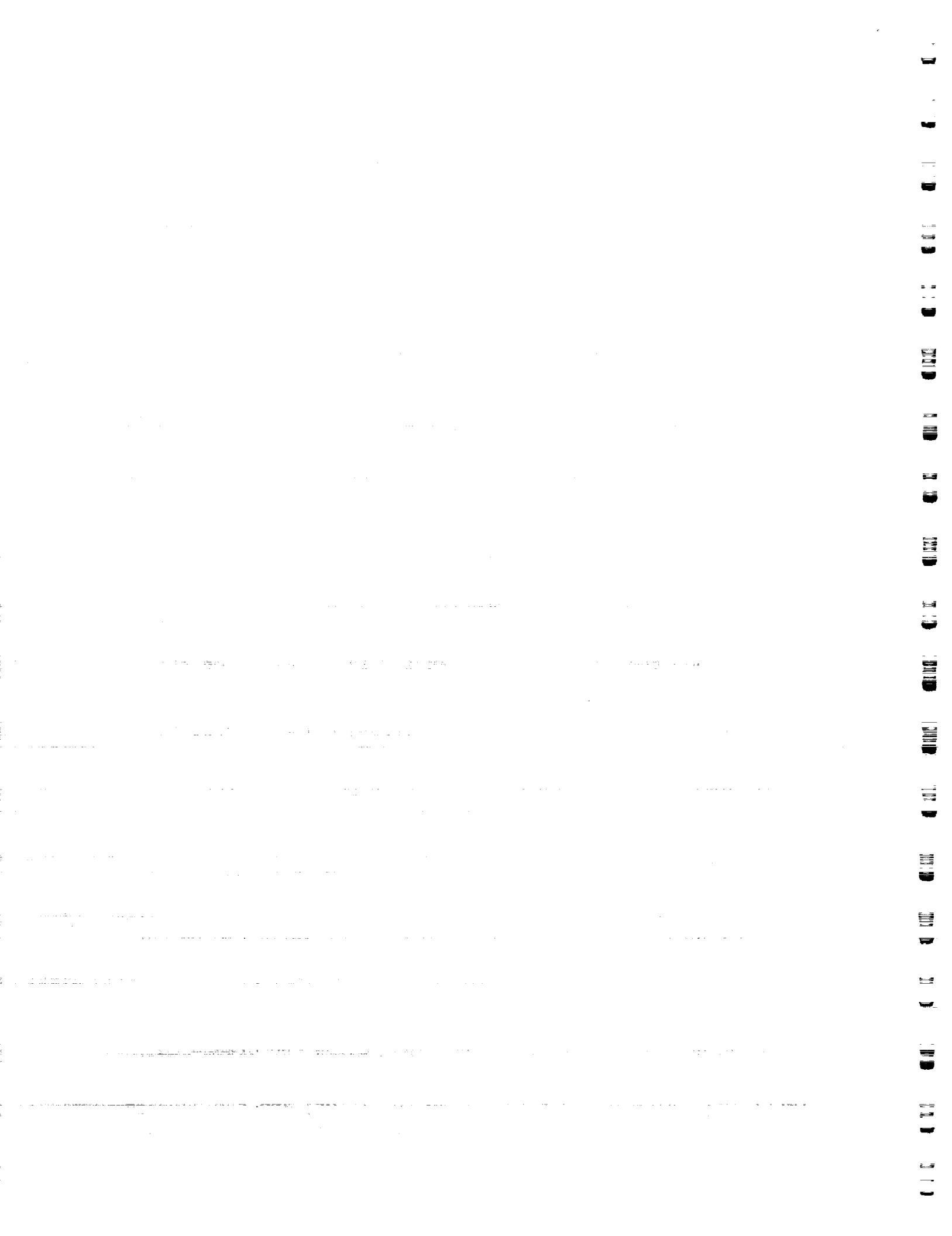
We can relate the normalized signal X given in Eq. (4) to the brightness sensation B by assuming that as the sensation varies from -1 to $+1$ the brightness varies from 0 to 10 . Thus our brightness parameter would be comparable to Munsell value. By Eq. (4) the resultant expression for B would be

$$B = 5(1 + X) = \frac{10 P_1}{P_1 + P_0} \quad (5)$$

This is the same expression derived by Adams and Cobb^{12,13} in 1922 to show the effect of an adapting luminance P_0 on the apparent brightness of an object of luminance P_1 .

Thus it appears that there is strong evidence that Eq. (4) defines the proper gain control law of the receptor. However, it is simpler to discuss the adaptation process in terms of the assumption that the regeneration rate alone is used for gain control, as was indicated in Figure 1. Since the qualitative results are quite similar the simpler assumption will be employed.

Let us return to Figure 1. The signal delivered by the outer segment is fed to the inner segment where it is amplified by the gain K_2 to form the receptor output signal. This output is filtered to form the white-black (or luminosity) information and demodulated to form the blue-yellow and green-red chromaticity signals. To adjust the gain K_2 the output is rectified, probably by a full wave rectifier, and the average rectified signal compared with a reference level. The error



in output level, averaged over the control-loop time-constant (probably about 2 minutes for cones and 10 minutes for rods), is fed back to control the gain K_2 in such a manner as to reduce the error in level to zero.

Since the receptor acts as a balanced detector, it would have an output of essentially zero if there were no drift in the amplification process. However, because of the tremendous gain, the amplification processes would drift considerably unless appropriate measures were taken. One method of eliminating drift is to a-c couple the amplification stages, so that there is no signal transmission at zero frequency. The difficulty with this approach is that the time constant of the coupling network would have to be comparable or greater than the regeneration time constant, which is several minutes. Another approach is to feed back the average output through a slow bias control loop as is indicated in Figure 1. This feedback loop must also have a long time constant but it may be convenient to achieve it by chemical feedback means.

With the adaptation processes illustrated in Figure 1, the retina could slowly adapt to any fixed illumination level and keep the receptors in accurate calibration and optimized to work at that level. However it cannot correct for fast adaptation changes. Measurements made by Baker⁸ show that when a background light of 984 trolands is suddenly turned off, the threshold drops by a factor of 25 in 0.2 seconds to a final threshold that is equivalent to a continuous light of 5 trolands.*

What produces this rapid change of threshold? One postulate is that it is achieved by data processing in the neurons which follow the receptors. The argument against this is that the dynamic range is so great. The adaptation level (984 trolands) is about 200 times that of the threshold after turning

* The threshold was measured by means of a flash of light of 0.02 seconds. Since the integration time of the receptors is 0.1 seconds the short flash of light is equivalent to a continuous light of one-fifth its intensity.

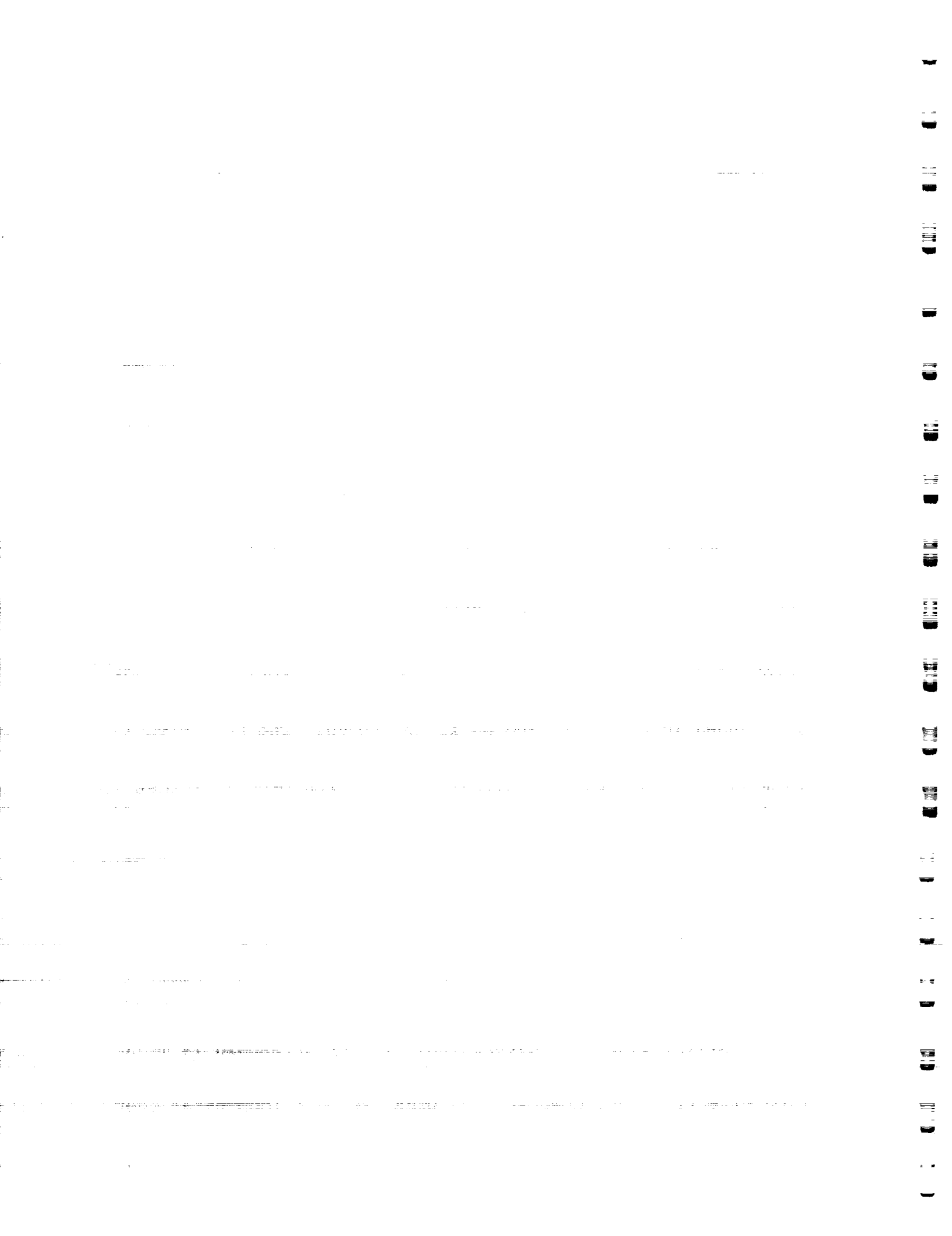


off the adapting light (5 trolands). With the adapting light turned on, a light intensity many times greater than the adaptive level could be carried without saturating the visual system, or affecting the state of adaptation. Thus the ratio of maximum to minimum light intensity is much greater than 1000 to 1. To achieve this performance without changing the gain in the receptors when the light is turned off would require that the receptors and following neurons have a tremendous linear range, which seems very unreasonable.

This argument leads to the conclusion that some form of fast feedback control is used to change the gain in the receptors in order to produce this rapid 25-to-1 increase in sensitivity after the adapting light is removed. How can this be achieved? The logical argument is that the outputs from the receptors are directly summed together to form weighted average signals which are used in feedback loops to control gain and bias in the receptors. These feedback loops would produce the primary effects of simultaneous contrast.

Figure 2 gives a block diagram showing a possible description of how the fast feedback loops might work. The block diagram of the outer segment of the receptor is the same as that shown in Figure 1, and so is not shown. The rectified outputs from the various receptors are summed together to form an average rectified signal which is fed back in a fast feedback loop to control the gain. The luminosity signals from the various receptors are summed in a similar summing network and fed back to control the bias.

Let us see how the receptor would respond to turning off the light if it were controlled as indicated in Figure 2. Initially the receptors are nearly balanced in output. When the light is turned off the outer segments are unbalanced and deliver a strong negative current that drives the inner segment amplification into saturation. If the threshold is measured at this instant it would be higher because of the saturation effect. Soon, however, the bias feedback loop takes over.



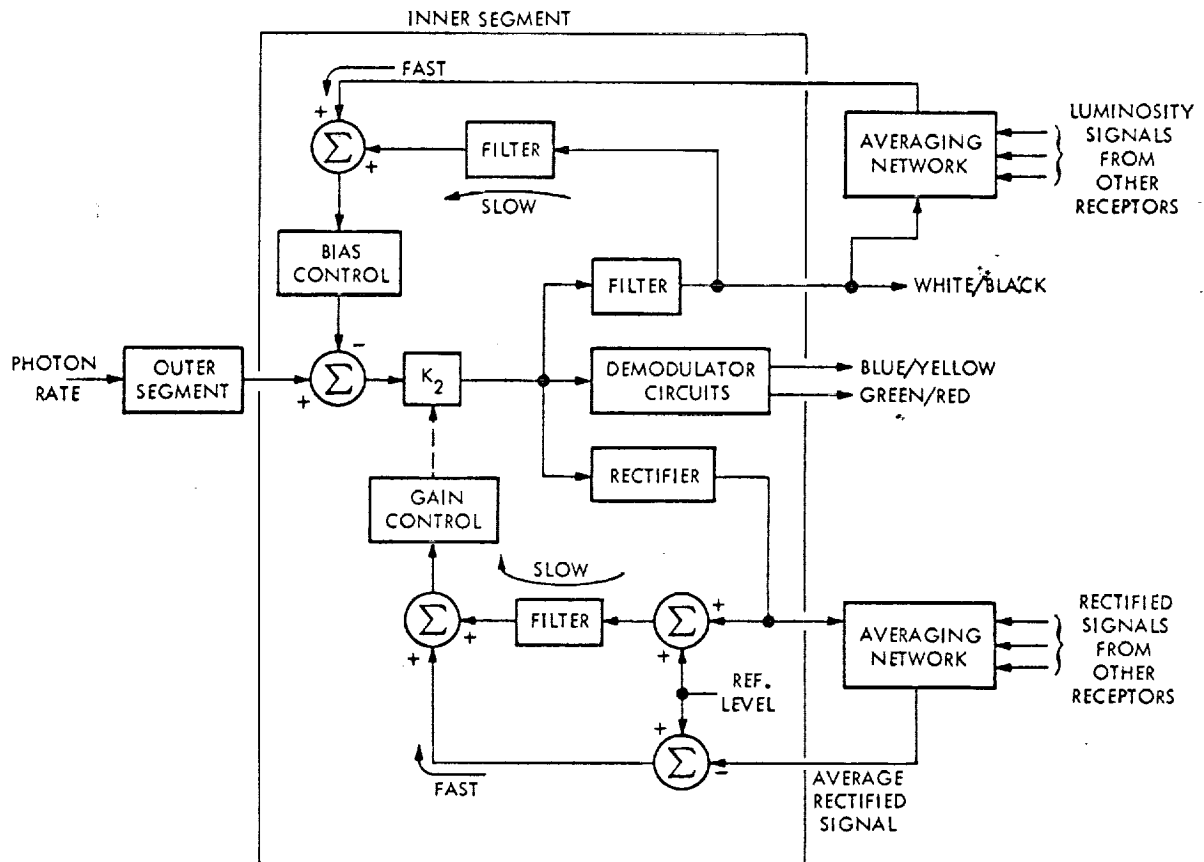


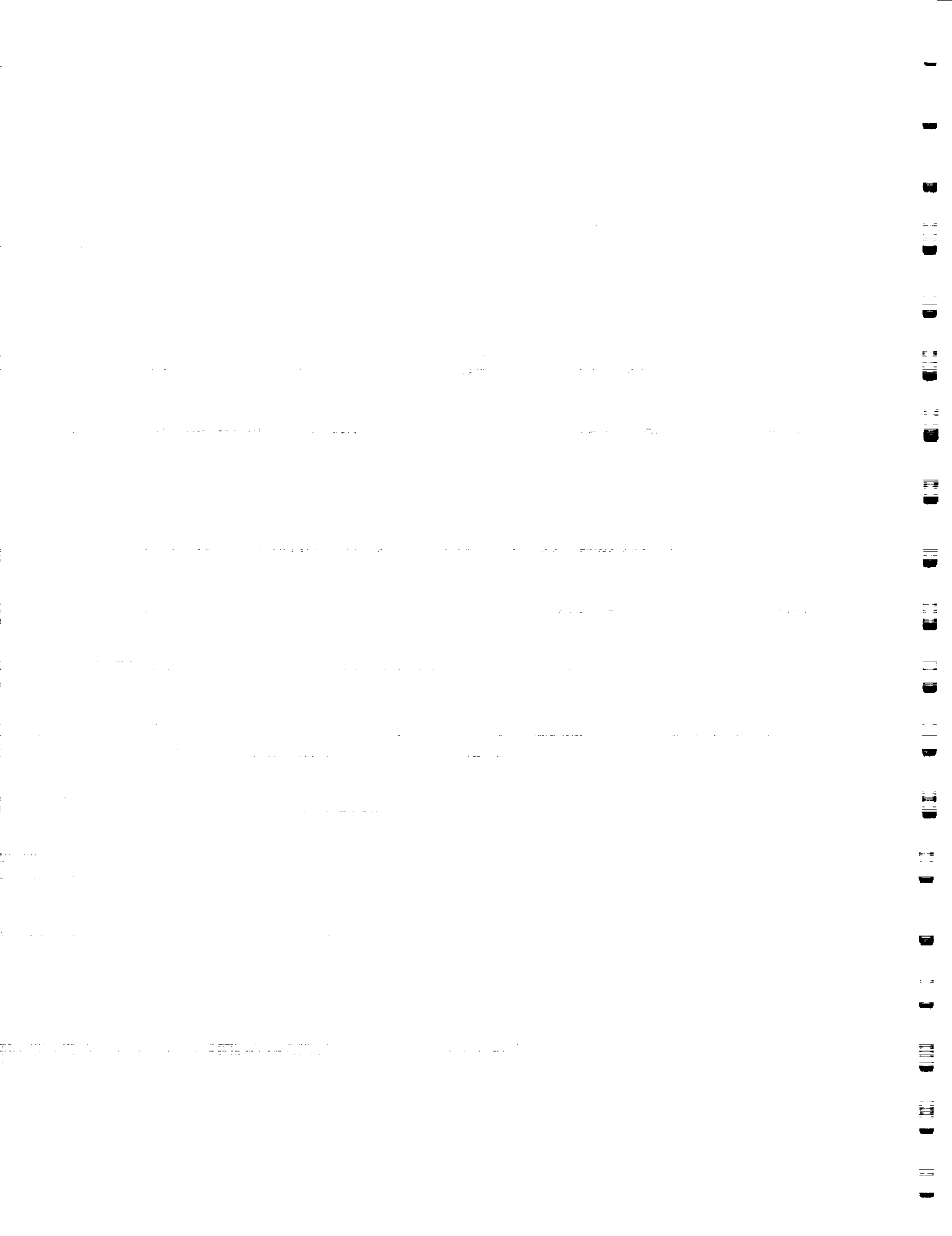
Figure 2. Possible Feedback Circuits For Providing Simultaneous Contrast and Calibration of Receptors

It compensates for the unbalance and brings the signal back into the center of the amplification range. The gain control increases the gain in the inner segment, which results in a drop in threshold.

The final value of threshold, which is reached a second or two after turning off the light, is established by the noise produced in the regeneration process.⁸ When the adapting light is on, the threshold is evidently established by the noise level in the neurons that follow the receptors. Turning the adapting light off, would allow the receptor gains to be increased, which would reduce the relative effect of noise in the following neurons. This would cause the threshold to drop to the value established by shot noise in the pigment regeneration current.

Baker⁹ has made measurements of the threshold levels during early dark adaptation, and these are in agreement with the operation described above of the postulated gain and bias control system for the receptors.

On the basis of straightforward systems arguments a model has been developed of the achromatic adaptation processes of the receptors which appears to be consistent with experimental data. Although this model is probably inaccurate in certain details, it should serve as a good first approximation. Let us now generalize this model so that chromatic adaptation is performed, and examine how well it satisfies our knowledge of the chromatic adaption process.



SECTION 3

CHROMATIC ADAPTATION

The achromatic visual adaptation model can be generalized to perform chromatic adaptation by making the following assumptions:

- (1) The regeneration current and gain control process in outer segment are localized effects that occur prior to the scanning process.
- (2) The fast feedback loops in the inner segment that control gain and bias are sufficiently fast to follow the modulation of the waveform produced by the scanning process.

As will be shown, applying these assumptions to the achromatic adaptation model provides a very simple and effective explanation of chromatic adaptation.

Figure 3 shows how the sequential-contrast effects of chromatic adaptation would be produced by the action of bleaching in the receptor. Diagram (A) represents the energy density as a function of position across the cone for what will be assumed to be the background illumination. This light will generate the bleaching current density shown as curve (1) in Diagram (B). If the receptor were initially adapted to a light have a flat spectrum, curve (1) would define the output signal from the cone.

As the cone adapts to the illuminant, the bleached pigment builds up in accordance with the pigment density shown in Diagram (C). This produces a regeneration current density shown as curve (2) in Diagram (B). The regeneration current density (2) subtracts from the bleaching current density (1), to produce a net current density (3) which is zero. Thus the net output current from the receptor has been reduced to zero with adaptation.

If the adapting light were turned off, the regeneration current (2) would be the net current. This has the opposite

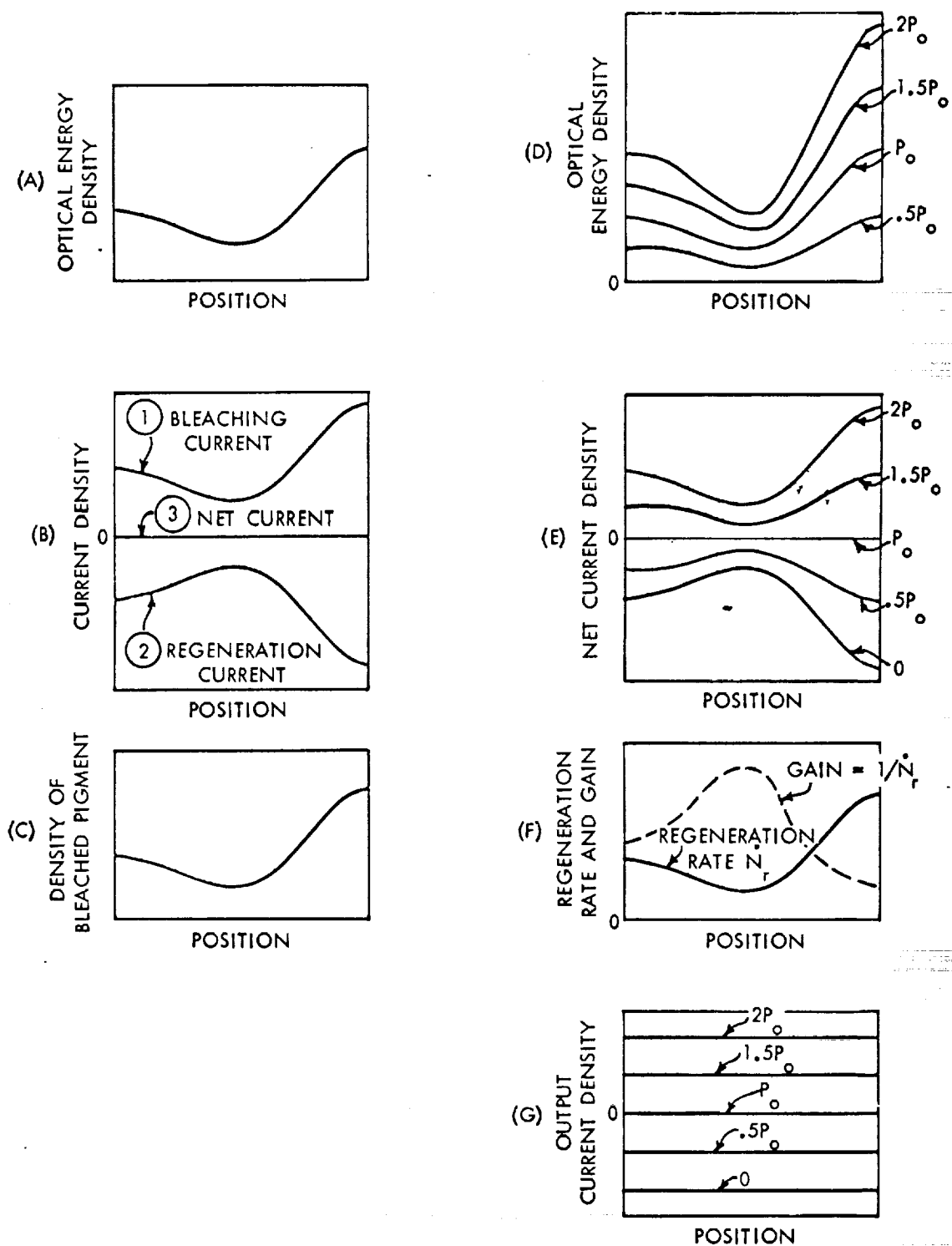
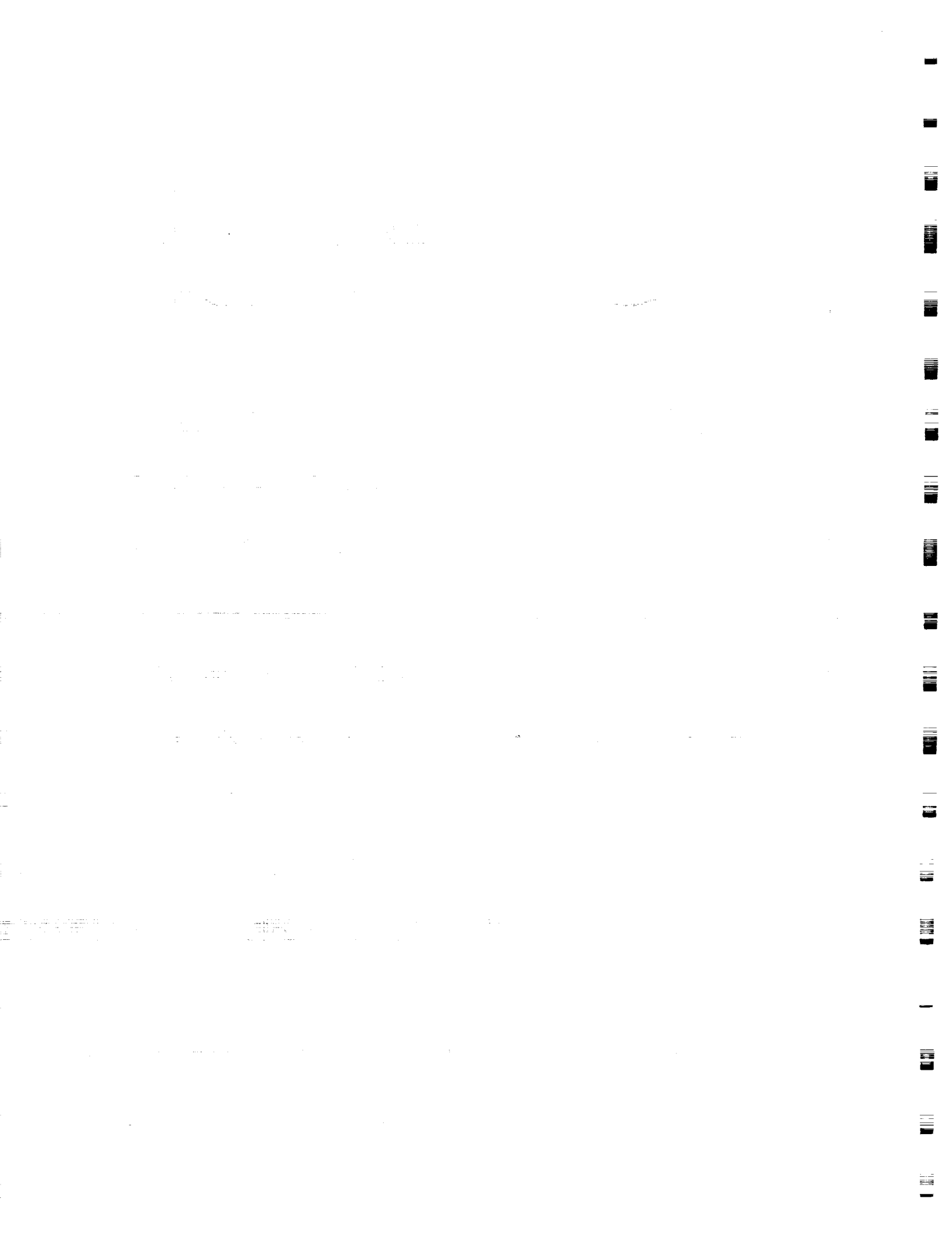


Figure 3. Effect of Sequential Color Contrast



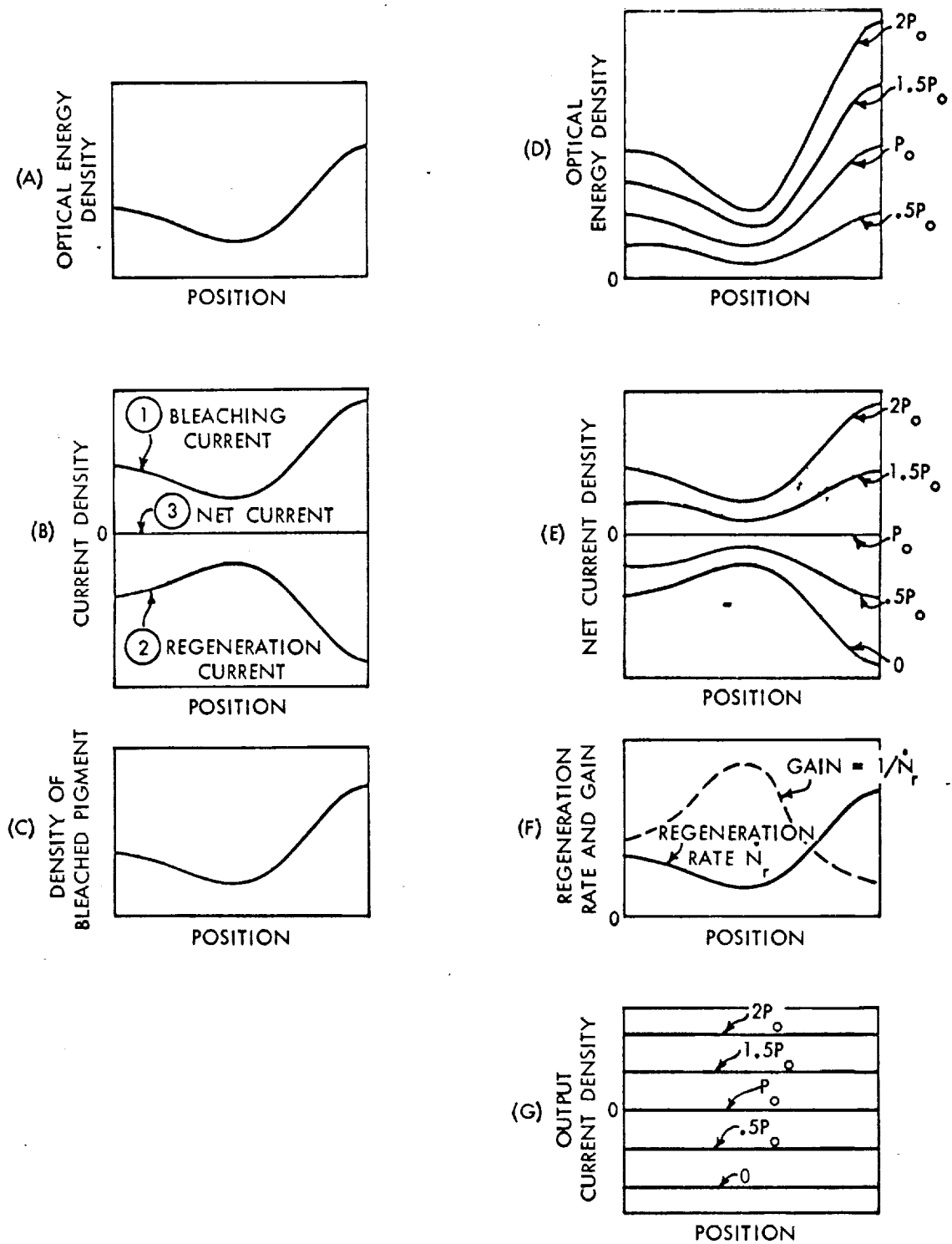


Figure 3. Effect of Sequential Color Contrast

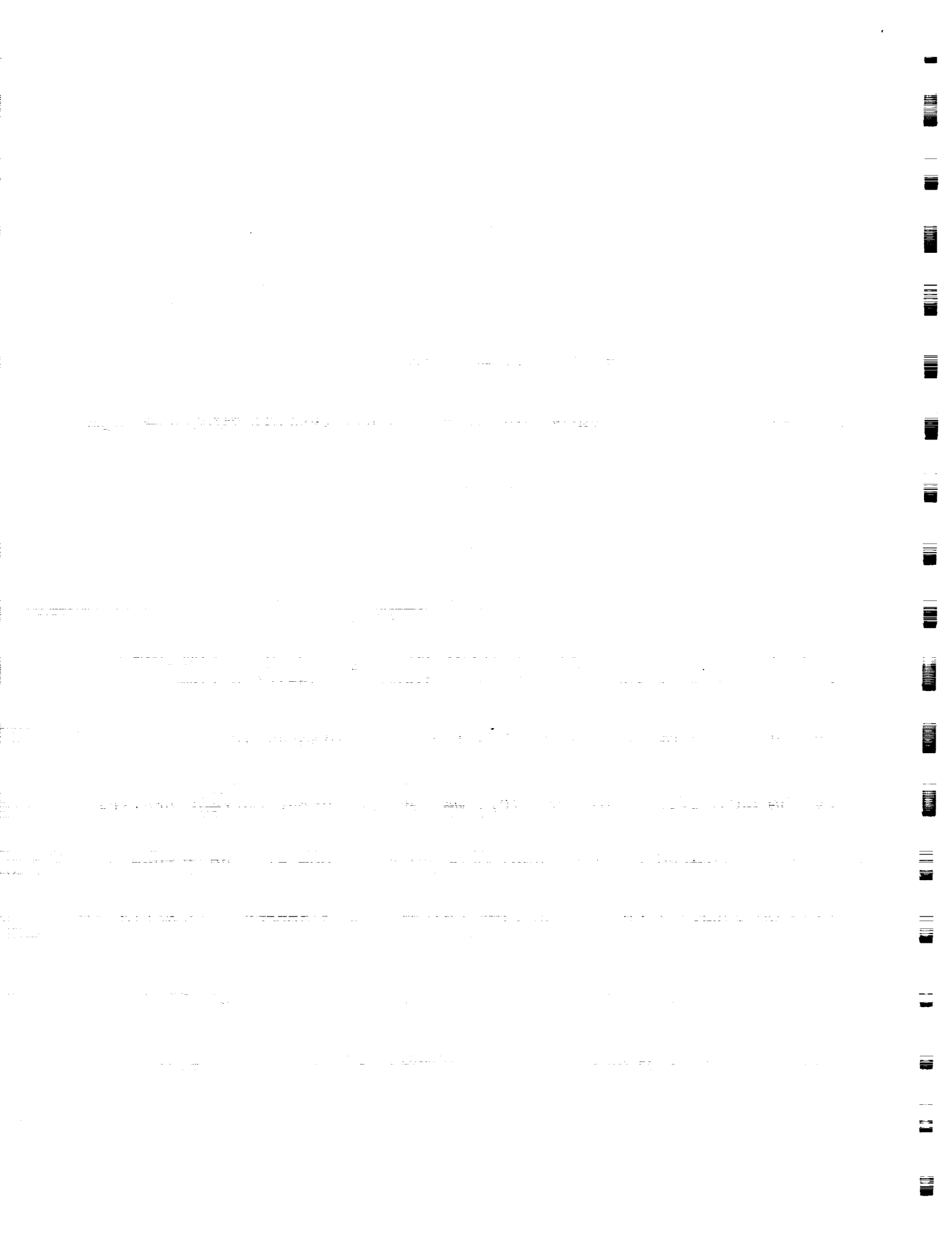
spatial variation to that of the adapting illuminant, and so would give a signal corresponding to the complement of the illuminant color. This effect is responsible for complementary after images.

Let us assume that the eye is in a completely achromatic situation, so that the spectra from the various objects vary only in intensity. The intensities are assumed to be 0, $0.5 P_0$, P_0 , $1.5 P_0$, and $2P_0$, where P_0 is the average illumination intensity to which the cone has become adapted. Diagram (D) shows the energy densities across the cone produced by the light from the five objects. Diagram (E) shows the net current densities produced in the cone. For the average illuminant the net current density is zero as it was in Diagram (B). For the black object of zero light intensity the net current density is the regeneration current that was given as curve (2) in Diagram (B).

Diagram (F) gives a plot of the regeneration rate \dot{N}_r , which is the magnitude of the regeneration current (2) shown in Diagram (B). Now Figure 1 shows that the gain in the amplification process is adjusted to be proportional to $1/(\dot{N}_r + \epsilon)$ or approximately to $1/\dot{N}_r$. If we assume that there is localized amplification across the cone, the amplification gain would vary across the cone as shown by the dashed $(1/\dot{N}_r)$ curve in Diagram (F).

If we multiply the current density curves of Diagram (E) by the gain plot in Diagram (F), we get the output current density curves shown in Diagram (G). It is these curves that define the signal generated by the scanning process. Since all the curves are flat, the receptor would deliver constant signals for all the five objects. Thus all the five objects would appear achromatic, which is what is required. The effect of bleaching in the outer segment constantly adapts the cone so that an object with the same spectrum as the average spectrum will appear achromatic.

In the above discussion we chose a gain control that is proportional to $(1/\dot{N}_r)$ rather than a more likely gain control



that is proportional to $1/(N_r + N_i)$. If the latter gain control were used, the results would be the same except that the vertical spacings between the constant curves of Figure 3G would be varied. The effect would be to compress the curves for intensities greater than unity so that the maximum positive and negative variations of the output current density would be equal (i.e., the normalized output current would always be within the limits of -1 and $+1$).

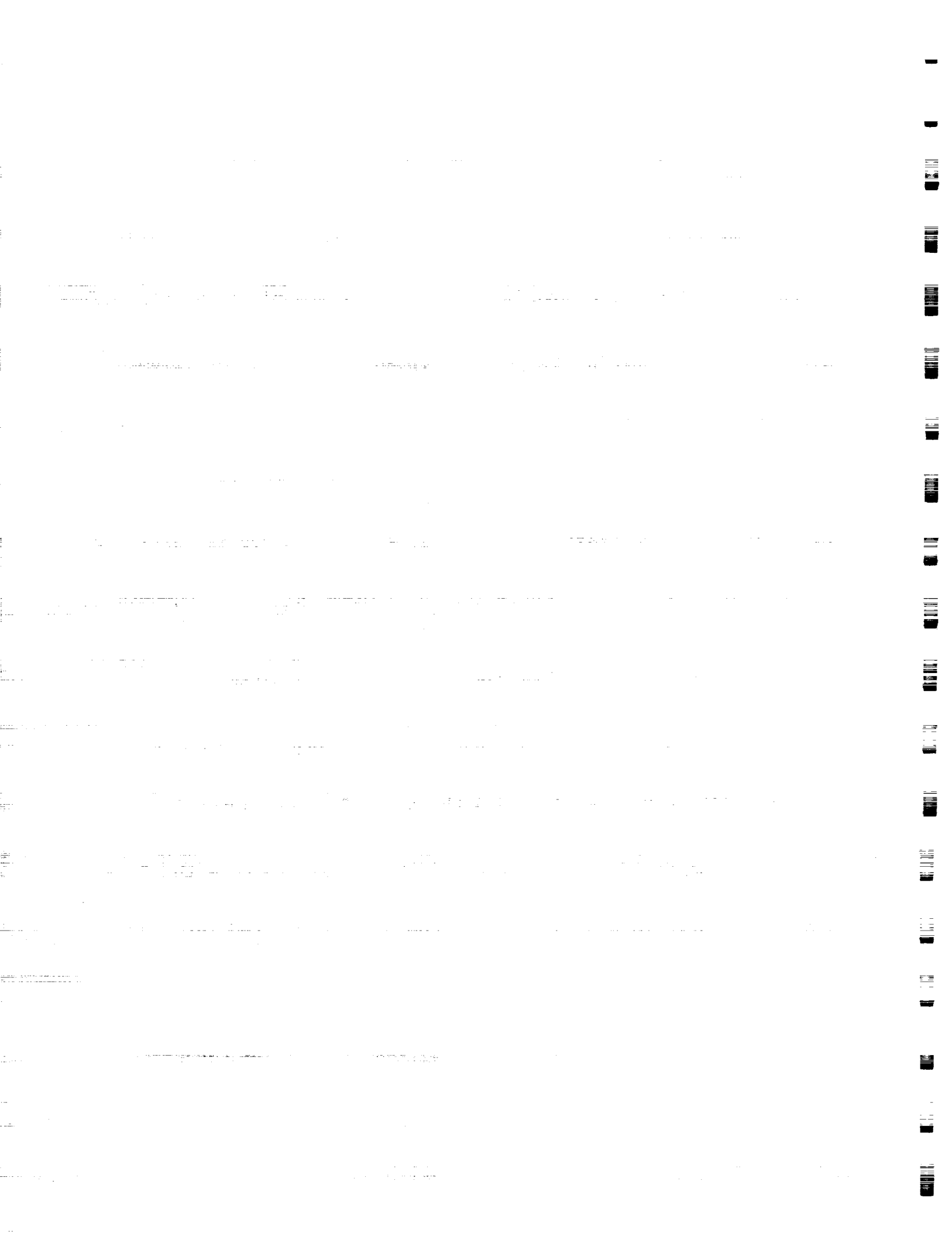
If the background illumination should suddenly change, the outer segments would no longer be adapted to the average illuminant and so modulated signals would be delivered from achromatic objects. This effect is compensated for by the simultaneous contrast effects performed by the fast feedback loops in the inner segments, so that the net signals delivered by the receptors are not modulated.

Figure 4 illustrates the chromatic adaptation action produced by simultaneous contrast. Let us assume that the eye is initially adapted to a flat energy density curve which produces the bleaching current density shown by Curve (2) in Diagram (A). The regeneration current would then be curve (3). Now let us assume that the average bleaching current is changed from curve (2) to curve (1). The net output current density from the receptor for an average intensity object would change from zero to curve (4).

Diagram (B) shows the current densities that would occur for our five achromatic objects. The curve for P_0 is the same as Curve (4) in Diagram (A), and the curve for zero intensity (the black object) is the same as curve (3) of Diagram (A).

When the field scans back and forth across the cone the five current densities of Diagram (B) generate the five modulated waveforms shown in Diagram (C). These signals are fed into the inner segment where they are amplified.

The signal from all the receptors are fed into a summing network to form an average signal.. If the eye is looking over a balanced field of view, the average signal from the receptors will correspond to the average intensity P_0 . Thus the average



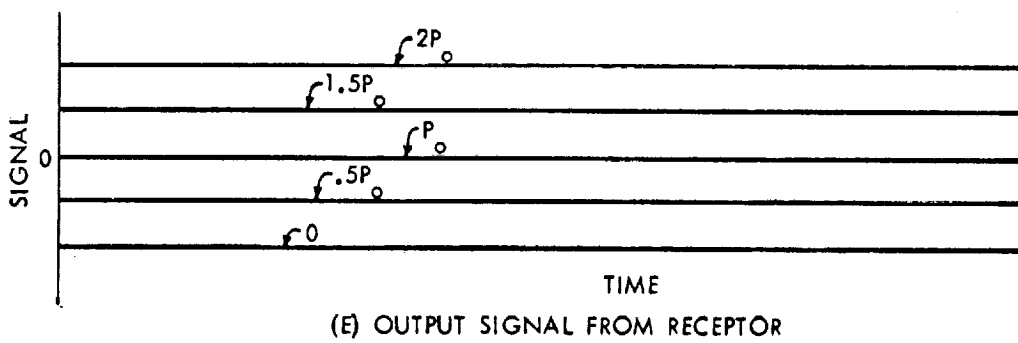
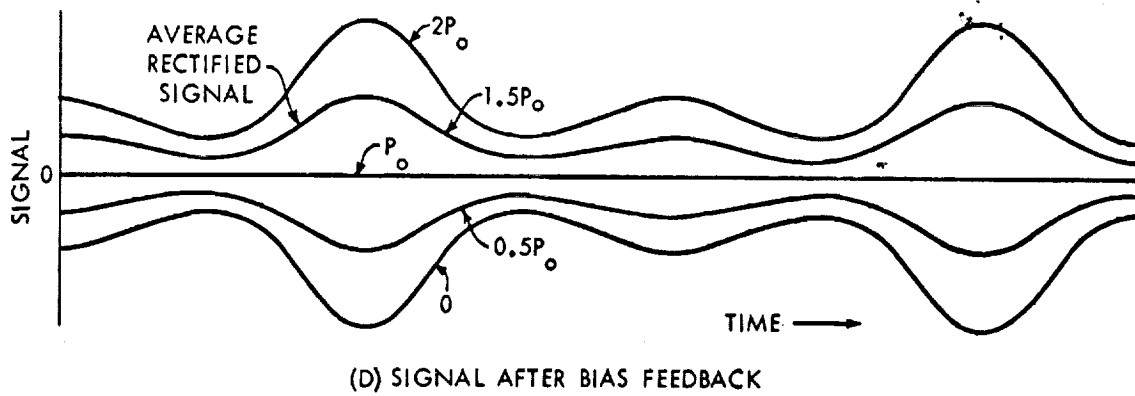
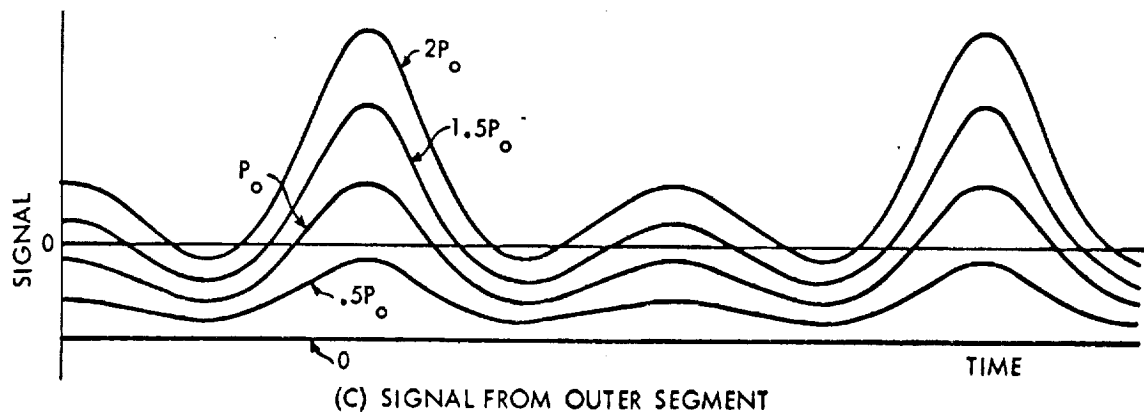
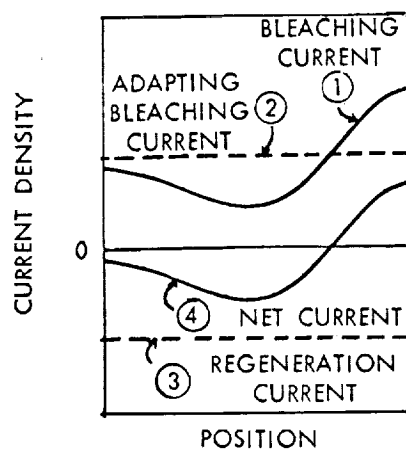
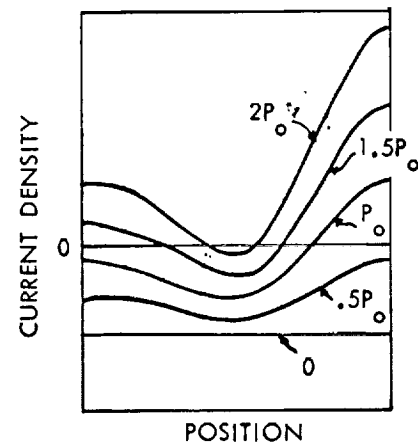


Figure 4. Effect of Simultaneous Color Contrast

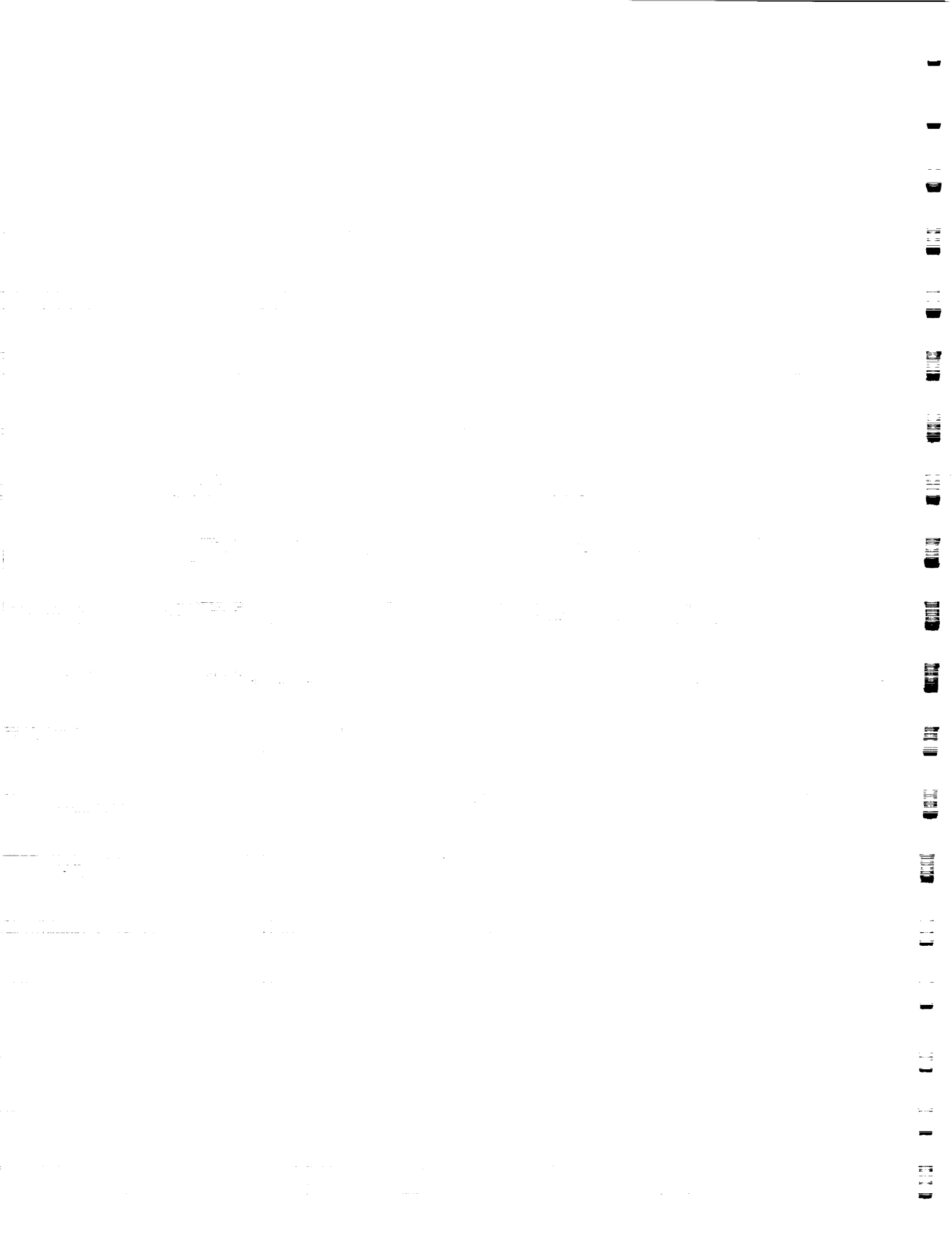


A) CURRENT DENSITY FOR
AVERAGE INTENSITY



B) CURRENT DENSITIES
FOR FIVE INTENSITIES

Figure 4. Effect of Simultaneous Color Contrast (continued)

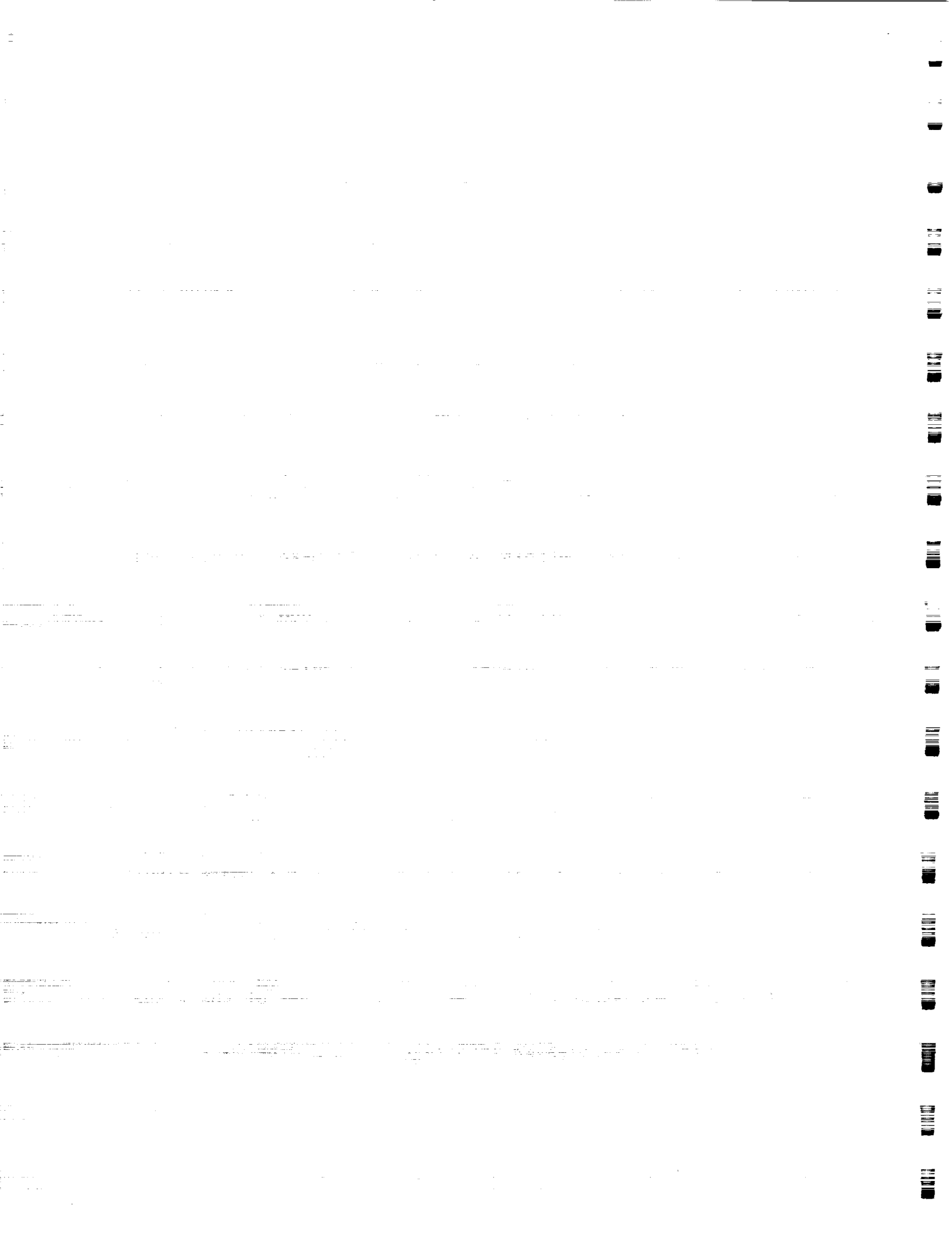


signal from the summing network will be proportional to the curve for P_0 . This average signal is fed back in the bias feedback loop. The effect is that a bias voltage is generated which is equal to the negative of the curve for P_0 , and reduces the response to the P_0 curve to zero. The signals after the bias feedback point are as shown in Diagram (D). The signal for intensity P_0 is zero and that for zero intensity (the black object) is equal to the negative of the curve for P_0 shown in Diagram (C).

The signals in Diagram (D) are amplified by the gain K_2 . The output signal from the receptor is rectified and the rectified signals from the receptors are summed together to form an average rectified signal. If the gain K_2 were kept constant the average rectified signal would be proportional to the curve in Diagram (D) for $1.5 P_0$. However, the fast gain control loop uses as a reference the average rectified signal, which is the response to the curve for $1.5 P_0$, and controls the gain K_2 to make the response to the curve for $1.5 P_0$ a constant. The result is that the gain K_2 is reduced when the curve for $1.5 P_0$ rises, and vice versa, so that all the waveforms are effectively divided by the curve for $1.5 P_0$. This results in stripping the modulation from all the waveforms, and so the output signals from the receptor are as shown in Diagram (E). These curves have no modulation components and consequently all the achromatic objects are seen as achromatic.

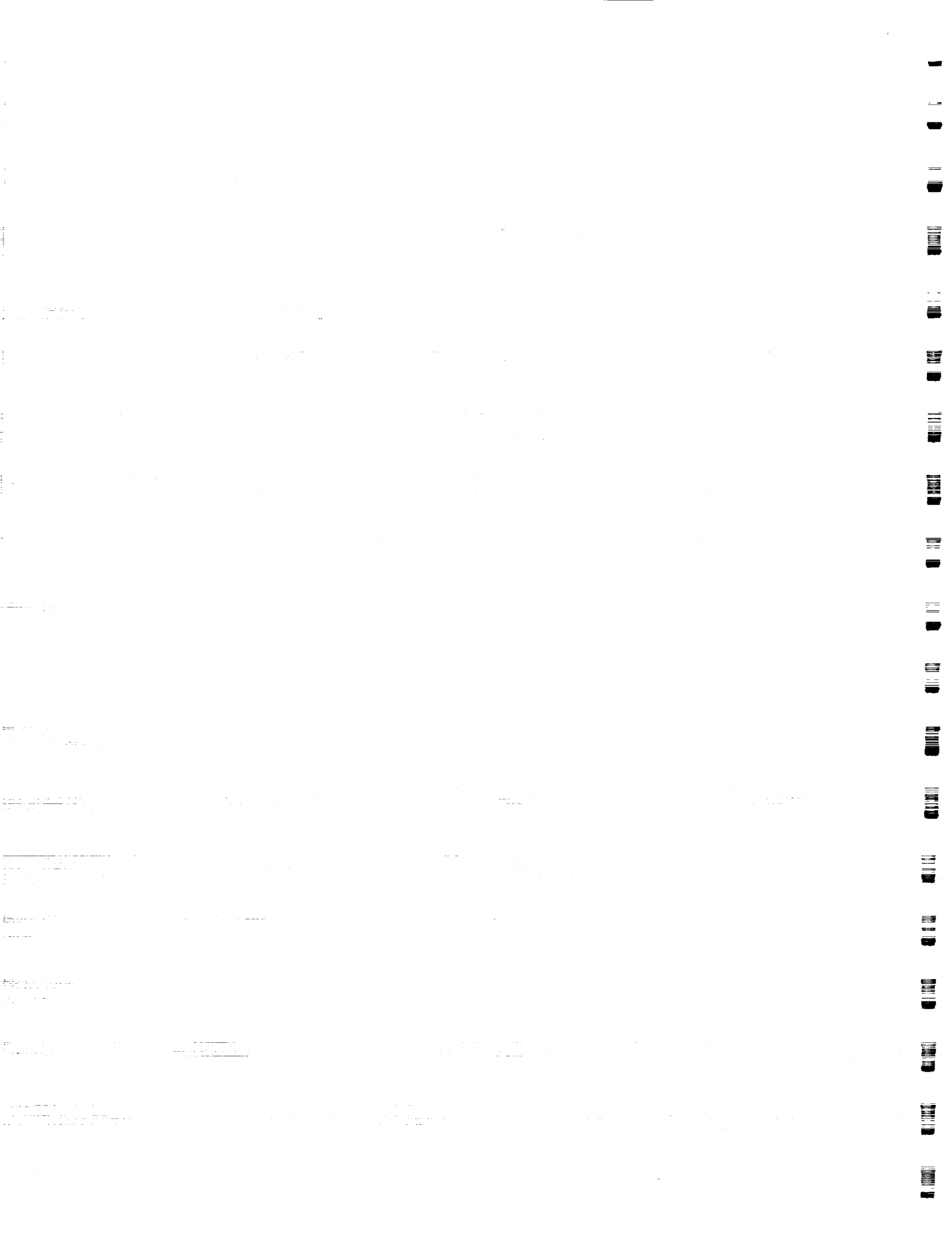
Thus it has been shown how the basic control functions required to achieve achromatic adaptation in the receptors can also provide chromatic adaptation. These functions under normal conditions will make achromatic objects always appear achromatic, and, with regard to the achromatic scale, will keep white objects white and black objects black.

Helson¹⁴ demonstrated the great effectiveness of the visual system in keeping achromatic objects achromatic. His experiments showed that, if the background illumination is a mixture of a monochromatic light and only 7 percent white light, achromatic



objects will appear achromatic. However, when the white light is reduced below that point, achromatic objects lighter than the background take on the color of the illuminant while achromatic objects darker than the background take on the color of the complement of the illuminant.

The result that Helson achieved with the extreme monochromatic illuminant is explainable by Figure 3. Diagram (E) shows that the current density for the average signal P_0 has no spatial variation, that for brighter lights has the spatial variation of the illuminant and that for dimmer lights has the variation of the complement of the illuminant. These variations are normally eliminated by the gain control shown in Diagram (F). However, if the variations are too severe, which presumably occurs with extreme monochromatic illuminants, the gain variation can only partially compensate for the spatial variation of the illuminant, and so the observer sees achromatic objects as chromatic.



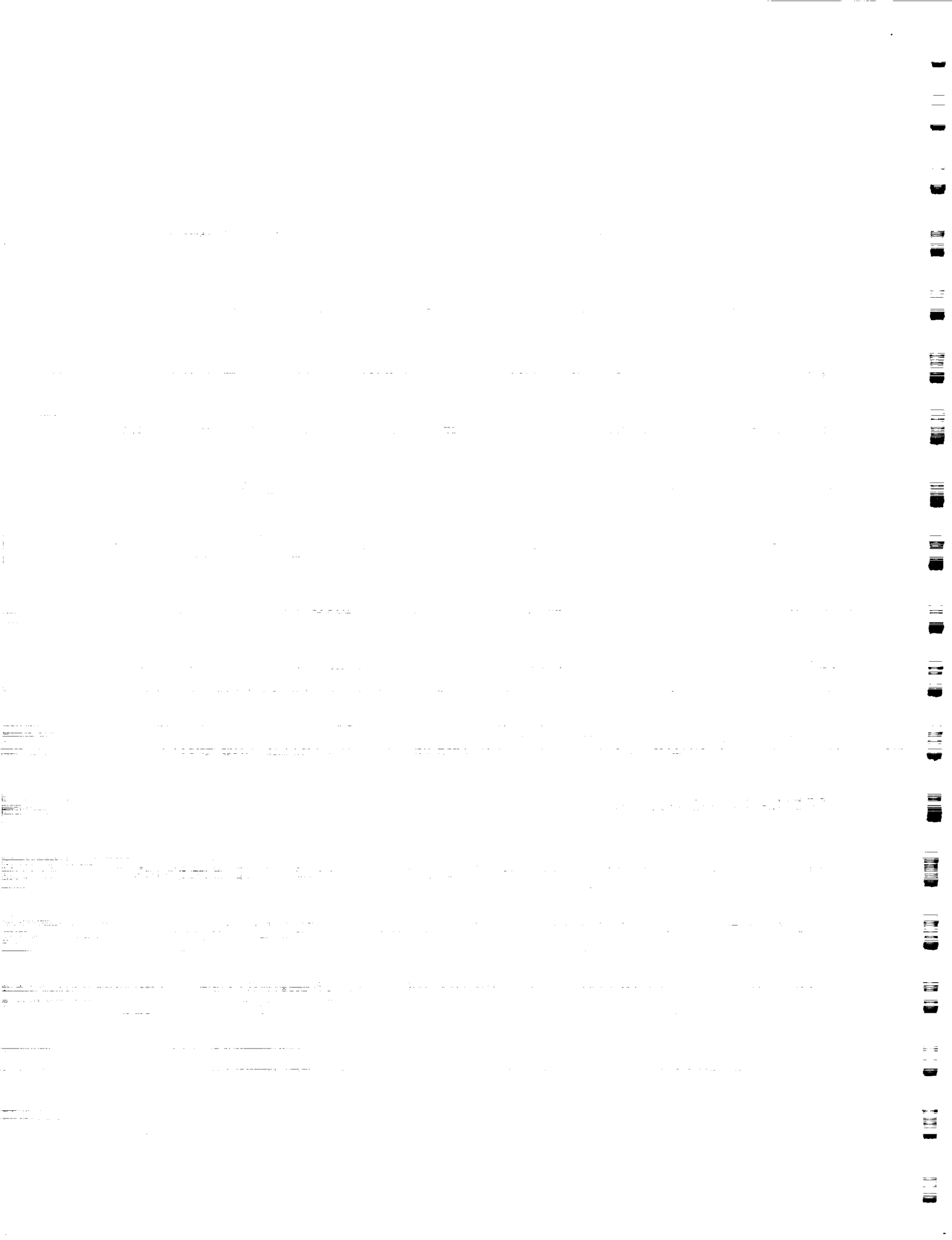
SECTION 4

IMPLICATIONS OF CHROMATIC ADAPTION MODEL

The important point to draw from the preceding discussion is that a straight-forward extension of the Spectral Scanning theory leads one to the inescapable conclusion that the main aspects of chromatic adaptation would be executed prior to the demodulation processes that produce the trichromatic color signals. In other words, chromatic adaptation would be performed, not in terms of three-dimensional color data, but rather in terms of the spectral patterns, defined by the spatial energy distributions and modulated waveforms, which have a much higher dimensionality. It is somewhat as if the visual system performed chromatic adaptation in terms of the spectra themselves.

Therefore, the Spectral Scanning theory is not a three dimensional theory of color vision. The final color signal that is generated is three dimensional, but the data processing associated with chromatic adaptation, which has such a great effect on what colors are actually seen, is implemented in terms of data of much higher dimensionality. Thus this theory raises a fundamental question concerning the validity of using three-dimensional color matches as the basis for defining the color vision process, particularly when one is trying to describe the effects of adaptation.

The real issue is accuracy. The adaptation processes proposed in the Spectral Scanning theory have a number of feedback effects that keep the visual system in accurate calibration. Direct comparisons between objects is made by the eye in terms of the spatial energy distributions and the modulated waveforms, which may be considered to be quasi-spectral data. These direct comparisons yield the difference in the quasi-spectral data, and it is this difference information that is demodulated to form the trichromatic color signals. Consequently the system is

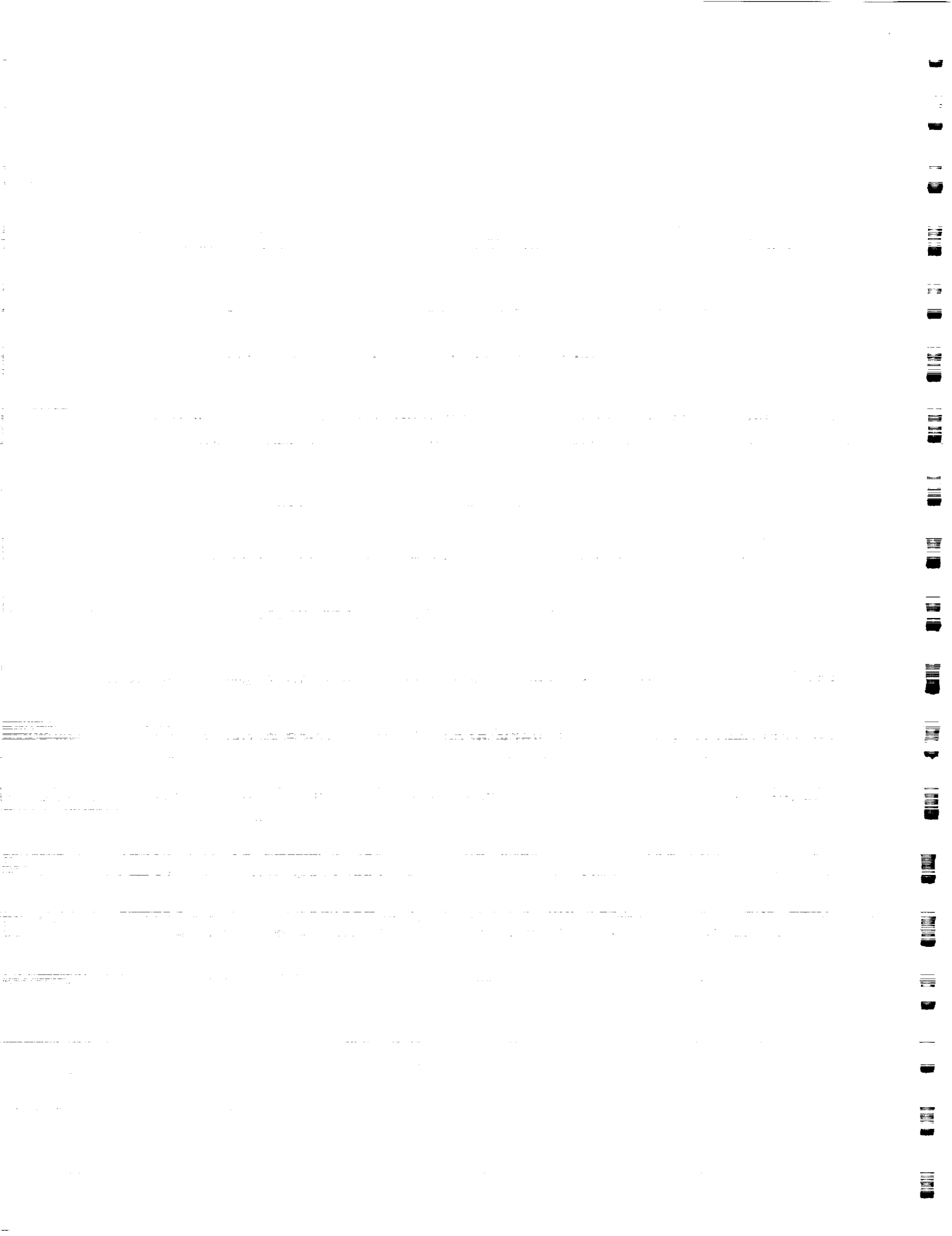


capable of detecting in a reliable manner very small differences in spectra.

The purpose of a visual system is object identification, and so it is optimized to detect the reflectivity of an object, not the spectrum of the light emanating from it. The Spectral Scanning theory proposes that the visual system achieves this result by forming the reflectivity information directly in the optical detection process. The adaptation operation performed in the outer segment of the cone by the photopigment bleaching compensates for the effect of the illuminant spectrum (provided that the illuminant spectrum is the average spectrum to which the cone has become adapted) and therefore generates a current distribution that corresponds directly to the reflectivity of the object. The adaptation effect of the bleaching also tends to compensate for differences in the spectral characteristics of the individual cones, so that the signals generated in different cones by the same object are much more alike than are the static spectral characteristics of the separate cones.

By means of the adaptation effect achieved by photopigment bleaching, the visual system is able to detect very small amounts of chromaticity in the reflectivity characteristic of an object. An achromatic object will very accurately produce a d-c signal in each cone, and a slightly chromatic object will produce a slight but unmistakable a-c component. If there is no change of the relative spectrum from the average there is zero modulation on the signal generated in the outer segment of the cone; any change of the spectrum from the average produces modulation. Thus the visual system has inherent self regulation with respect to chromaticity, which allows it to adapt over a very large dynamic range and still achieve very high accuracy of chromaticity discrimination.

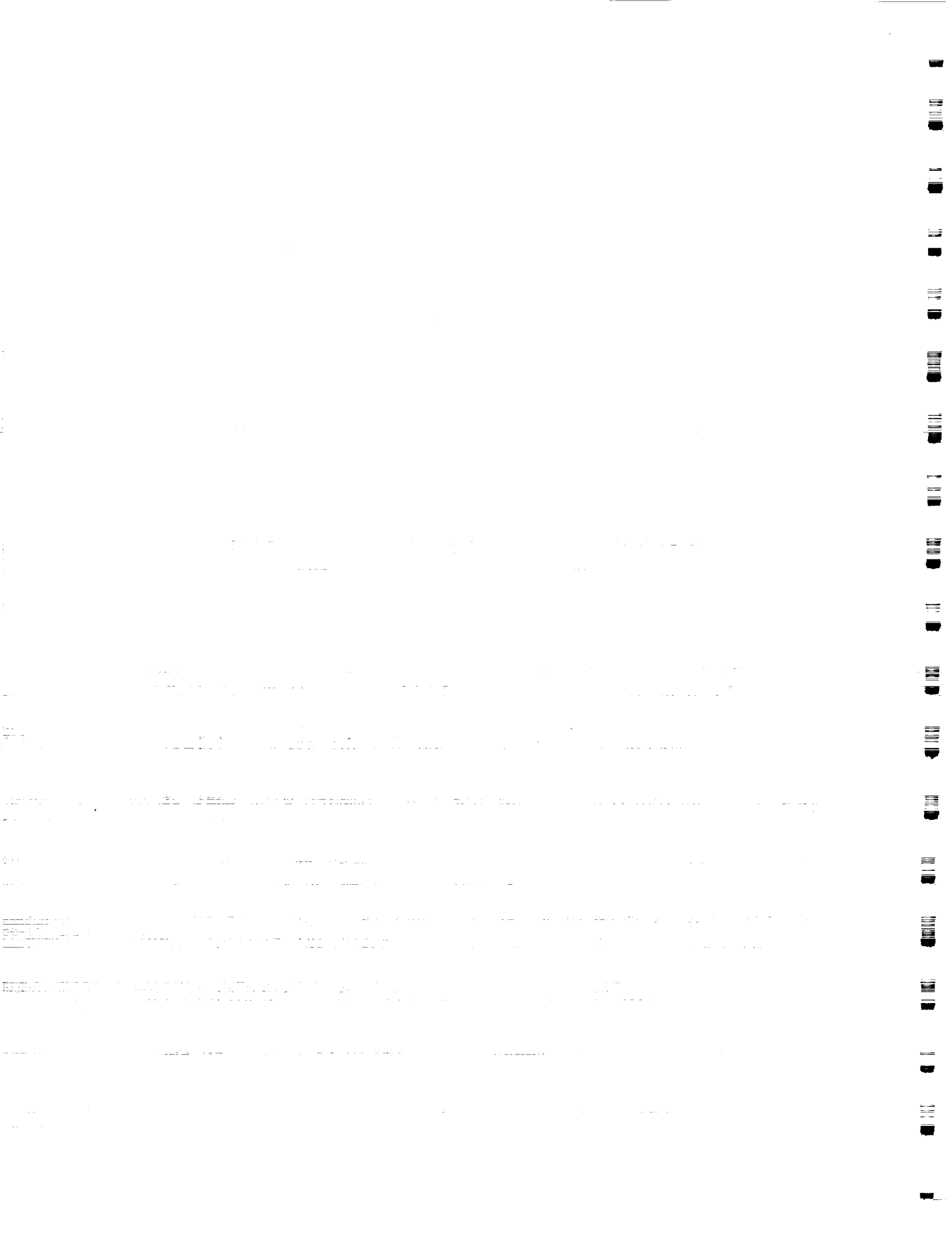
When the eye is viewing a natural image, the interactions of the signals from neighboring objects produces simultaneous



contrast effects. The spectral patterns from the objects, as represented by the modulated waveforms, are compared directly, and the differences between them are formed. It is the difference in the spectral pattern information that is actually demodulated to form the trichromatic signals. By working with differences in spectral patterns, the eye is able to detect very small differences in the chromaticity of neighboring objects. This gives rise to the enhancement in spectral resolution that is achieved by simultaneous contrast.

The preceding discussion shows how a visual system based on the Spectral Scanning theory could achieve very high fidelity in discriminating between objects of different reflectivity spectra and still be able to adapt to compensate for large variations in the intensity and chromaticity of illuminant. In contrast, it appears very doubtful that a visual system based on the Trichromatic theory could achieve anything approaching this high degree of performance.

The Trichromatic principle is employed in the design of color television cameras. In color television, the elements in the three camera channels are accurately matched to a precision that is certainly impossible to achieve with the flesh and blood components of the eye, and yet the color fidelity technically achievable in a color television system (ignoring economic considerations) does not ever compare with that of human vision. Besides, the instantaneous dynamic range of a color television camera is very low compared to the eye, and there is no mechanism in the optical detection itself (i.e., ignoring the effects of an iris or filter in front of the camera) that can allow it to adapt to different average levels of light. It is obvious that the eye cannot use component precision to achieve accuracy of spectral discrimination, as is employed in color television. Rather, the eye must rely on natural feedback processes. The author is unable to see how such feedback processes can be incorporated within the framework of the Trichromatic theory.



By processing the spectral information in a single channel (as predicted by the Spectral Scanning theory) the eye could achieve very accurate discrimination among objects having different reflectance spectra. An important consequence of this is that the spectral data processing would have a dimensionality much higher than three, and it is this much higher dimensionality that represents one of the basic mathematical differences between the Spectral Scanning theory and classical theories of color vision.



SECTION 5

COMPARISON WITH CLASSICAL COLOR VISION THEORIES

The classical concept of the color vision receptor mechanism is based on the theory of Thomas Young¹⁸ proposed in 1801. In essence, Young postulated that the eye has three different types of photosensitive elements with different spectral absorption curves, and the signals from these elements produce the neurological color information. Today this principle, with the multitude of extensions that have been built on it, is generally referred to as the Trichromatic theory. If we also include those theories that have generalized the Thomas Young principle by allowing four or more photosensitive elements, we find that essentially all theories of the receptor mechanism of color vision have been based on the Thomas Young principle.

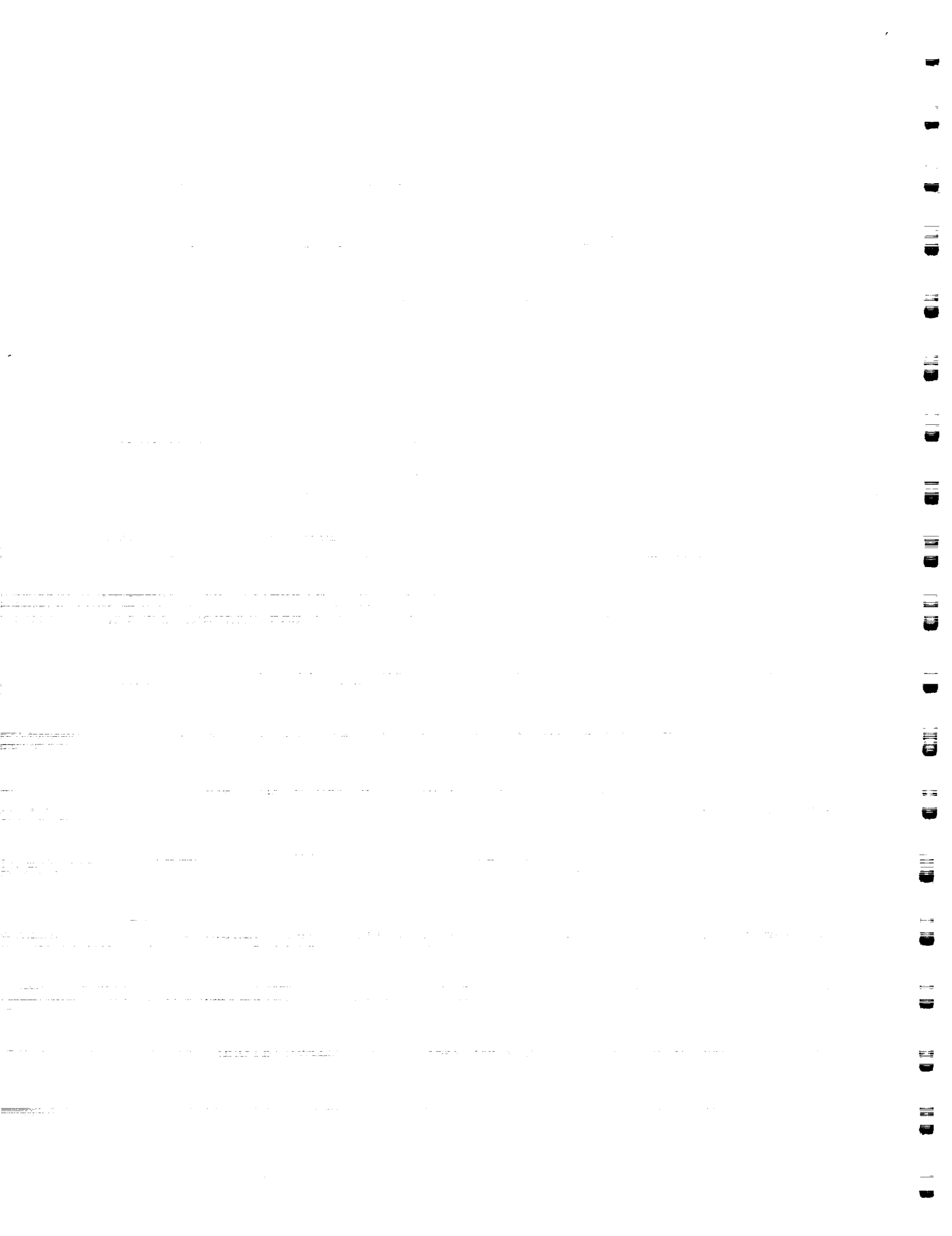
The concensus of opinion today favors the Trichromatic concept that the receptor mechanism is defined by only three different spectral sensitivity curves. A strong argument for this point of view was presented by Hunt¹⁵ in 1956, based on the phenomenon of constancy of metameric match. He reasoned that one can explain constancy of metameric match by assuming three photosensitive receptor elements with fixed spectral absorption curves. Spectra which match would evoke the same signals from each of these three elements, and so the spectra would always match regardless of how the signals from the photosensitive elements are processed. However, if there were four or more different types of photosensitive elements with independent spectral absorption curves, the responses of all these elements could not in general be the same for two matching spectra. Therefore if metameric matches were to be maintained, the sensitivities of the four or more separate channels would have to be inter-related in some precise and complicated manner, which seems unlikely.



Hunt pointed out that it would be possible for the retina to have four or more different types of cones, provided the spectral responses of the curves can be expressed as linear algebraic sums of the responses of three basic spectral sensitivity curves. Thus we could allow four types of cones having different mixtures of three basic photopigments, where the absorption curves of the three photopigments would define the basic spectral response curves. It is of course also possible for the retina to have only one type of cone, which contains within it separate regions that define the three photosensitive elements. The important point is not the number of cones but rather the number of independent spectral absorption curves.

Therefore, if we accept the almost universally believed receptor principle of Thomas Young, we are apparently forced to accept the Trichromatic principle, that there are three and only three basic spectral response curves in the visual photodetection process. This is equivalent to requiring that the photodetection process be three dimensional. We thus have a very clear point of distinction between the Spectral Scanning theory and the classical approach to color vision. The classical approach leads to the conclusion that the photodetection process is three dimensional, whereas the Spectral Scanning theory leads to the conclusion that the photodetection process has a greater dimensionality.

If the optical detection process of the Spectral Scanning theory is more than three dimensional, how do we reconcile that theory with the argument made by Hunt with respect to constancy of metameric match. The answer is that the signal processing of the multi-dimensional data is performed within a single channel, and all that is required for constancy of metameric match is linearity within that channel. Hunt's arguments apply when we assume the color information is processed along three or more separate channels.



If the data processing in the receptor were exactly linear, it would make no difference what the dimensionality of the detection mechanism was. However, the data processing of the multi-dimensional spectral data proposed in the Spectral Scanning theory has important, though small, non-linearities, and these non-linearities are essential in the achievement of accurate spectral discrimination. Nevertheless, the non-linearities are sufficiently small under normal conditions for metameric matches to be approximately constant, which is in agreement with experiment.

The two major non-linearities in the signal processing performed in the receptor are the controlled gain variations in the outer and inner segments of the cone. A simple qualitative understanding of the non-linear effects produced by these gain variations can be obtained by approximating the response of the gain control process in the outer segment.

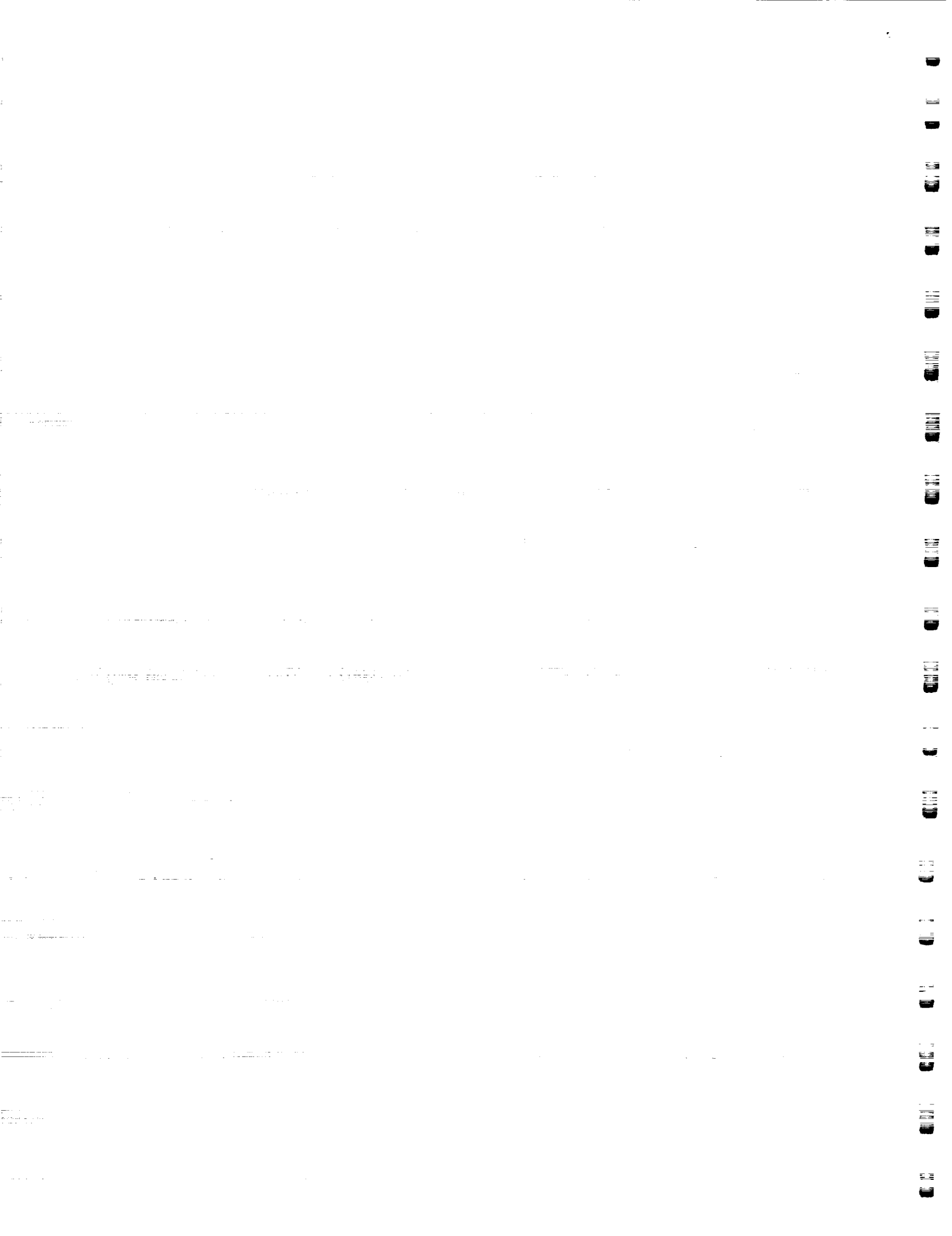
As a first approximation, assume as was shown in Figure 1 that the control varies the gain in the outer segment inversely with the regeneration current density R , which corresponds to the background (or time average illumination). The normalized signal X from the outer segment would then be

$$X = \frac{S - R}{R} = \frac{S}{R} - 1 \quad (6)$$

where S is the current density produced by the sample. Express the sample and regeneration current densities S and R as sums of the average densities \bar{S} and \bar{R} plus the modulation components ΔS and ΔR . Equation 6, can then be written as

$$(1 + X) = \frac{S}{R} = \frac{\bar{S} + \Delta S}{\bar{R} + \Delta R} = \frac{\bar{S}(1 + \Delta S/\bar{S})}{\bar{R}(1 + \Delta R/\bar{R})} \quad (7)$$

For convenience, the quantity $(1 + X)$ is considered rather than X . The ratio of the peak value of the modulation deviation, to the



average value, is roughly proportional to the saturation of the light. Thus the peak value of $\Delta S/\bar{S}$ is roughly proportional to the saturation of the sample light, and the peak value of $\Delta R/\bar{R}$ is roughly proportional to the saturation of the background illumination. If the saturation of the background illumination is not excessive, $\Delta R/\bar{R}$ is much less than unity, and Eq. (7) can be approximated as

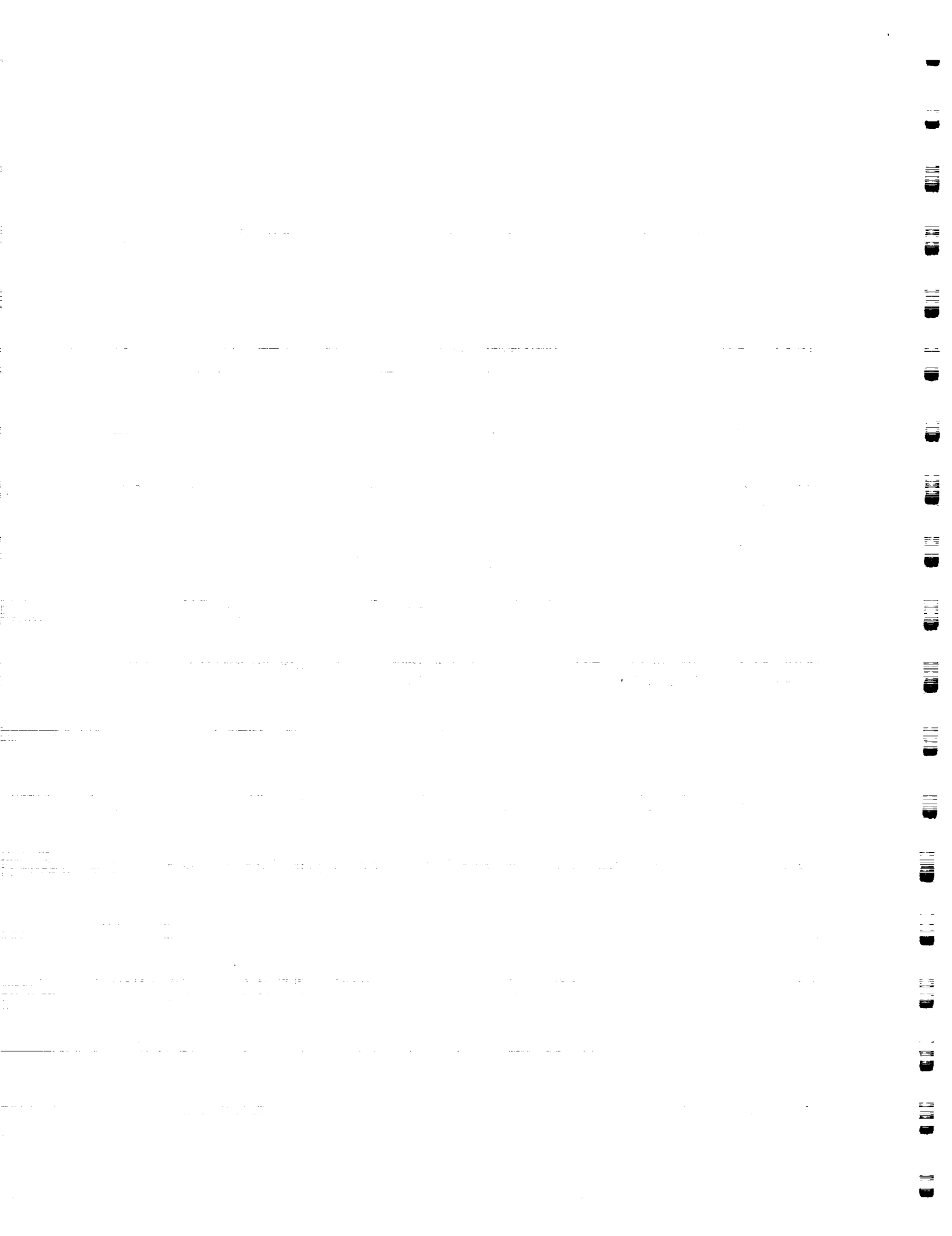
$$(1+X) \cong \frac{\bar{S}}{\bar{R}} \left[1 + \frac{\Delta S}{\bar{S}} \right] \left[1 - \frac{\Delta R}{\bar{R}} \right] = \frac{\bar{S}}{\bar{R}} \left[1 + \frac{\Delta S}{\bar{S}} - \frac{\Delta R}{\bar{R}} - \frac{\Delta S}{\bar{S}} \frac{\Delta R}{\bar{R}} \right] \quad (8)$$

The last term, $(\Delta S/\bar{S})(\Delta R/\bar{R})$ represents the non-linear effect in the gain control process. If the saturations of the background and sample lights are not both excessive, this non-linear effect is small.

Thus we would expect that non-linear effects would be small except under conditions of high saturation. When the lights are highly saturated we could expect there would be significant errors in metameric matches and in the operation of Grassman's laws. However, much more work is required before we can predict quantitatively how much errors would be expected.

If the two metamer spectra produced the same energy distributions across the cone there would be no change in the match regardless of non-linearities. However metamer spectra do not in general produce the same energy distributions across the cone. Nevertheless they do produce the same average value of energy distribution, because the luminosity signals for two metamer spectra must match (which is in accordance with Abney's law). This requirement that the d-c signals produced by metamer spectra are always equal regardless of non-linearities tends to minimize the effects of non-linearities in disturbing a metameric match.

Although the constancy of metameric matches is accepted as a solid foundation of color vision theory, there is little quantitative data to show how constant metameric matches actually are.

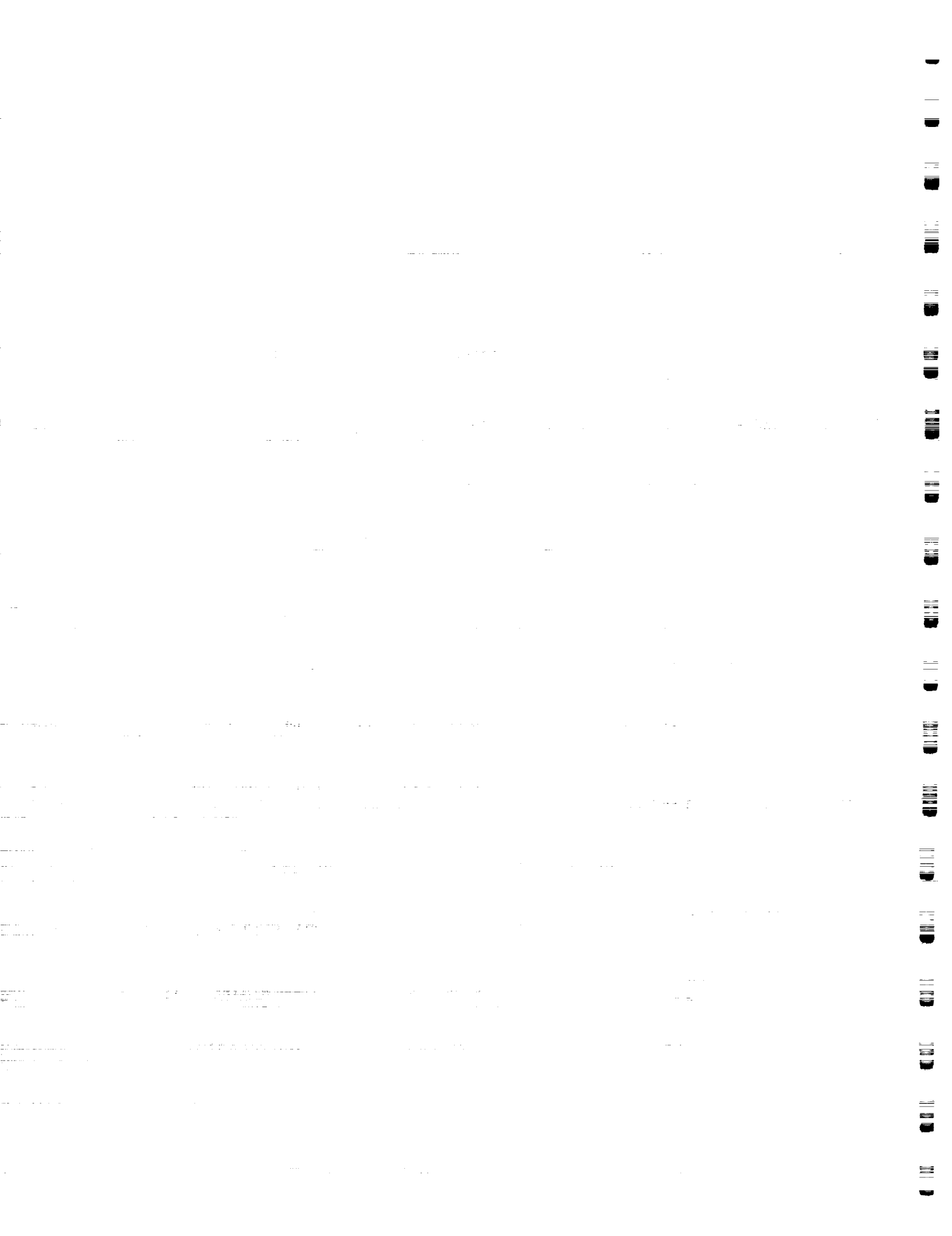


One of the problems is that the eye has much less accuracy in making a metameric match of two unlike spectra than it has in detecting small differences between two spectral that are nearly alike. For this reason it is difficult to separate departures from linearity of metameric match from the natural randomness of metameric matches, even though those departures are very significant visually.

As an example, consider the color matching experiments being performed by Stiles¹⁶ to develop a definition of the standard observer for a 10-degree field of view. The standard deviations of the settings of each primary is of the order of 10 percent for the group of observers, and 3 percent for a single observer, when the primary is relatively large. When a primary is small the standard deviation of its setting may be as large as 80 percent for the group of observers. When this deviation data is related to the resultant accuracy of the chromaticity diagram, the author found a maximum error of about ± 6 percent in x and y for the group of observers and nearly ± 2 percent for the single observer, occurring roughly at 500m μ .*

In contrast, the tolerance set on Munsell chips corresponds to ± 0.2 Munsell chroma, and the commercial tolerances for wool dyes is typically about ± 0.4 Munsell chroma.¹³ These tolerances correspond to x or y deviations in the CIE chromaticity diagram of about $\pm 1/3$ percent and $\pm 2/3$ percent for value 6 in the vicinity of illuminant C. The best match that can be made spectrally corresponds to less than ± 0.1 percent in x or y . For this reason the CIE chromaticity coordinates are specified to four significant figures, even though the metameric matches from which it is derived do not have anywhere near that accuracy.

*These represent $\pm 2 \sigma$, where σ is the standard deviation. If the standard deviations σ for x and y are equal, there is a 90 percent probability that the measured point on the chromaticity diagram will lie within $\pm 2\sigma$ of the specified x and y values.



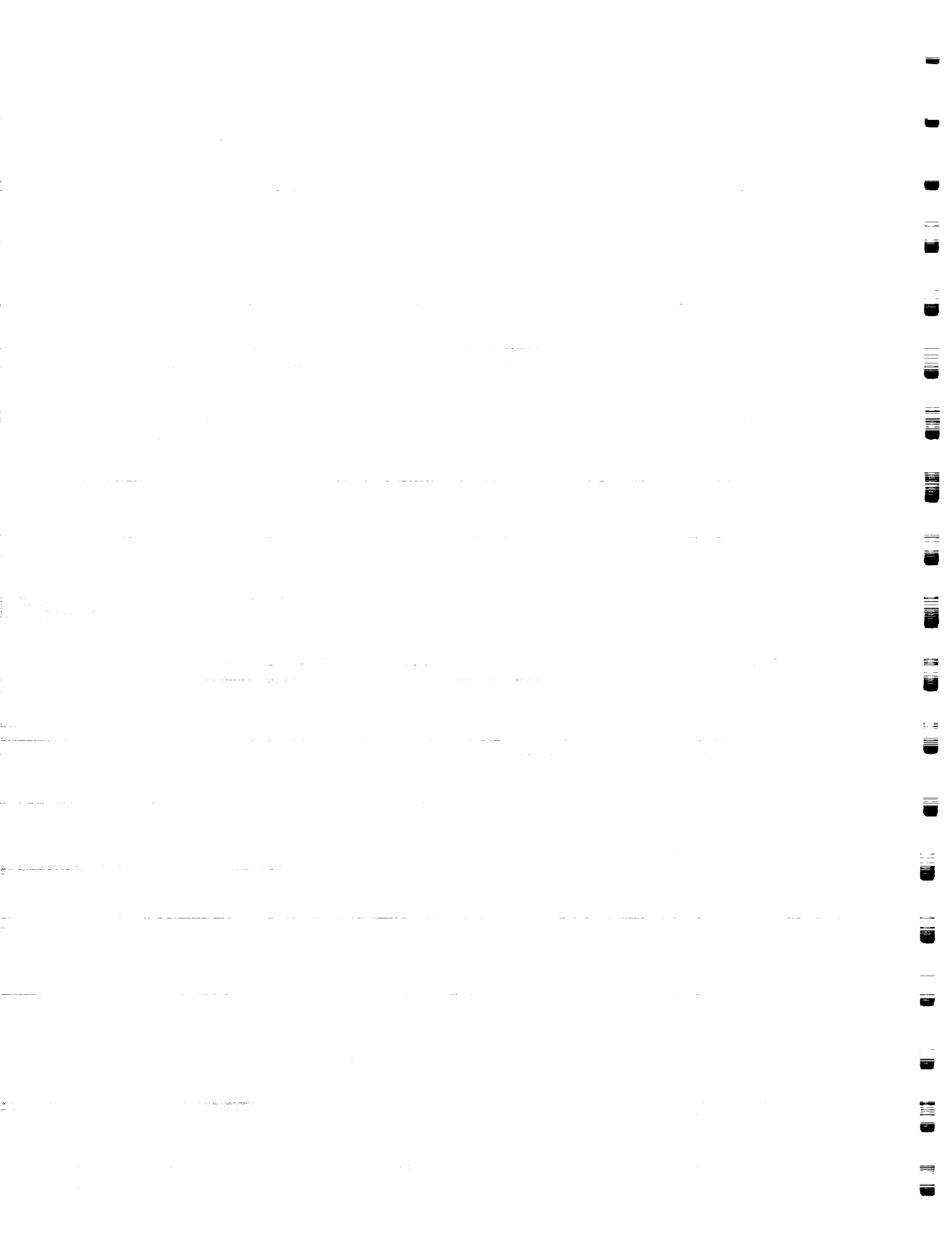
Thus, a color vision theory could allow significant percentage errors in metameric matches and Grassman's laws and still be in agreement with visual experiment. After all, there is no need for the eye to satisfy metameric matches with high accuracy. Rather, what the eye must be able to do is achieve high accuracy in the comparison of similar spectra. In addition, it should have high accuracy in maintaining constancy of color of natural objects independent of changes of illumination.

When we consider the problem of constancy of object color we enter the area of chromatic adaptation. An excellent summary of the present status of visual adaptation has been presented by Stiles.¹⁷ Metameric matches merely define equivalence classes between spectra; they say nothing about what color sensation the spectra evoke. Although the techniques for dealing with metameric matches are highly refined, the psychophysical description of chromatic adaptation is still in its infancy. Various color matching experiments have been performed to yield a quantitative description of chromatic adaptation, but they have encountered two major difficulties:

- (1) The measured data has a randomness much greater than that in standard color matching experiments.
- (2) There appears to be a great complexity in the underlying relationships between color sensation and adaptation conditions.

These experiments are usually made by means of binocular matching. However memory matching and the differential adaptation of different parts of the eye have also been employed.

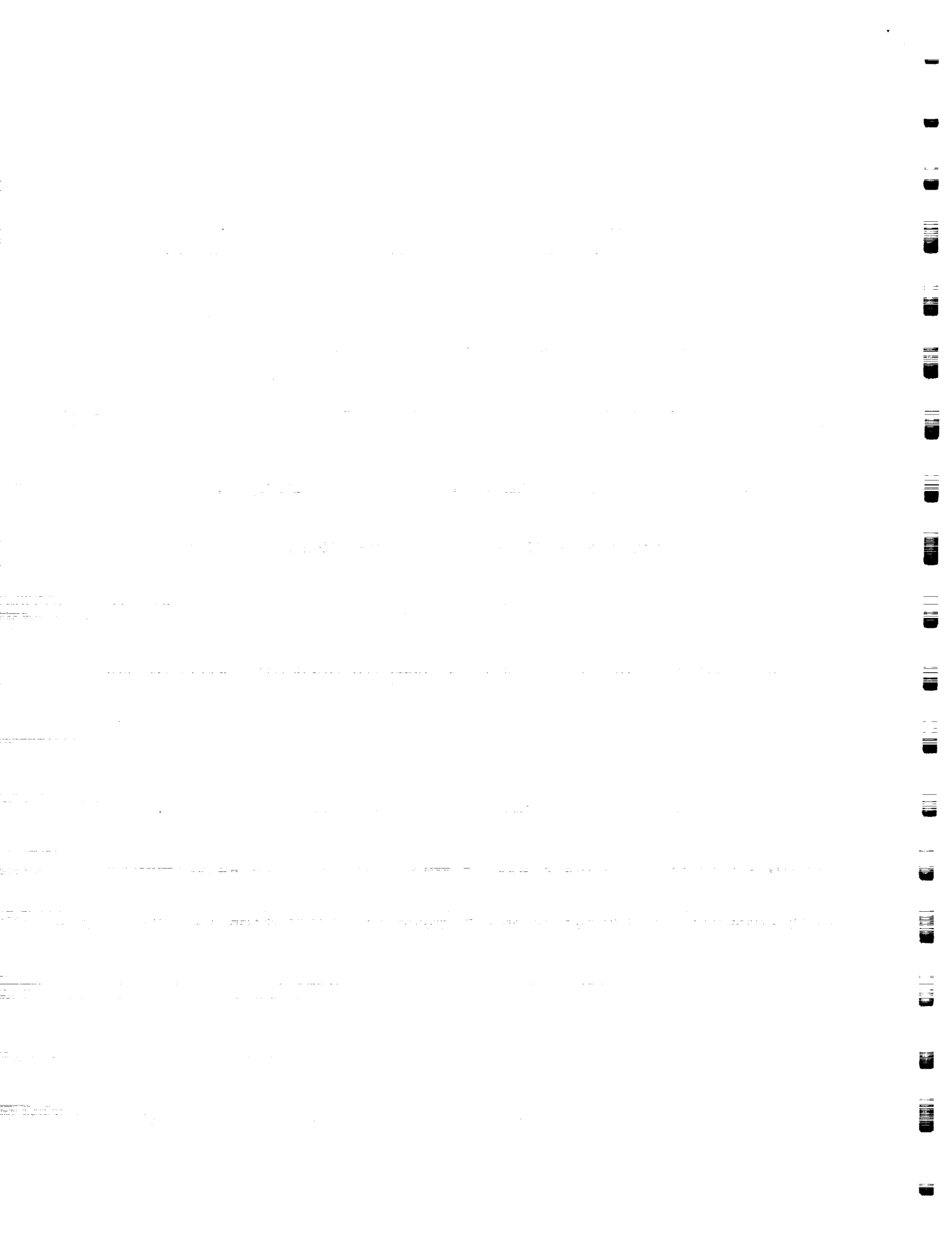
An important implication of the Spectral Scanning theory is that it provides a new approach to the problem of chromatic adaptation. The theory suggests that the apparent randomness and complexity observed in the chromatic adaptation experiments is the result of our attempt to define the multi-dimensional adaptation process in terms of three dimensional color matching experiments. The Spectral Scanning theory proposes that the eye



is achieving high accuracy of chromatic adaptation in a simple manner by performing the adaptation in terms of the multi-dimensional spectral patterns generated by the waveguide mode effects. However this inherent accuracy and simplicity appears as randomness and complexity when we measure the multi-dimensional chromatic adaptation phenomenon by means of three dimensional color matching experiments. Rather we must study the chromatic adaptation phenomena more in terms of the spectra themselves.

Our attempts to define the multi-dimensional chromatic adaptation process in terms of three dimensional color matching experiments may be likened to the proverbial two-dimensional man in Flat Land trying to interpret his experiences of the three dimensional world. Our two-dimensional man can observe a three-dimensional object only in terms of the cross section of the object lying within the plane of Flat Land. When a three-dimensional object passes through Flat Land, our two-dimensional man encounters a phenomenon of great complexity as he observes the varying shape of the cross section of the object lying within his plane, even though the three-dimensional object is very simple.

An important practical problem that is struggled with in the field of color standardization is that of defining a uniform color space. Very tedious empirical studies are being performed to improve our present color mapping techniques. However, since there are 10 million separately distinguishable colors, the problem is tremendous. A theory that could provide a better framework for color standardization by explaining the observed anomalies in color space would be very valuable. If we extend the Spectral Scanning theory by defining in precise terms the multi-dimensional manner in which chromatic adaptation is considered to be performed, we may well achieve a simple theoretical model that can accurately predict the apparently complex relationships of color space.



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